

Evolution of IR–Selected Galaxies in $z \sim 0.4$ Clusters

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ABSTRACT

Wide-field optical and near-IR (JHK) imaging is presented for two rich galaxy clusters: Abell 370 at $z = 0.374$ and Abell 851 (Cl0939+47) at $z = 0.407$. The new data are combined to produce colors sampling the 0.55–1.65 μm range in the rest frame. Galaxy catalogs selected from the near-IR images are 90% complete to a limiting magnitude approximately 1.5 mag below K^* . The resulting samples contain ~ 100 probable member galaxies per cluster in the central ~ 2 Mpc. Comparison with *HST* WFPC images yields subsamples of ~ 70 galaxies in each cluster with morphological types. Analysis of the complete samples and the *HST* subsamples gives the following results:

- 1) The optical– K colors of the cluster galaxies are bounded by a red envelope of E/S0s which follow a color–magnitude relation with a slope similar to the corresponding color–magnitude relation in present epoch E/S0s.
- 2) The $z \sim 0.4$ E/S0s are bluer than those in the Bower et al. (1992) Coma sample in the optical– K color by 0.13 mag for Abell 370 and by 0.18 mag for Abell 851. Our estimate of the systematic uncertainty indicates this color difference is significant at the 2–3 σ level. If real, the bluing of the E/S0 populations at moderate redshift is consistent with that calculated from the Bruzual and Charlot (1993) models of passive elliptical galaxy evolution.
- 3) In both clusters the intrinsic scatter of the known E/S0s about their optical– K color-magnitude relation is small (~ 0.06 mag) and not significantly different from that of Coma E/S0s as given by Bower et al. (1992), indicating that the galaxies within each cluster formed at the same time at an early epoch. These results support the paradigm in which the stellar population in cluster E/S0s is a function only of the galaxy mass and the lookback time.
- 4) Although the passive evolution models fit the $z \sim 0.4$ early-type galaxies

in the optical– K color, they fail to reproduce the observations at intervening wavelengths. When normalized at rest frame $\sim 1.6 \mu\text{m}$, the $z \sim 0.4$ E/SO’s are fainter than the model at rest frame $\sim 0.9 \mu\text{m}$, and brighter than the model (and than Coma E/SO’s) at rest frame $\sim 1.2 \mu\text{m}$. Such color differences are difficult to explain in terms of age or conventional metallicity effects.

5) The disk galaxies in Abell 851 are bluer and represent a greater fraction of the total sample compared to those in Abell 370. X-ray maps and large-field optical images indicate that Abell 370 is “older” than Abell 851, in the sense of showing a more relaxed distribution of galaxies and hot gas. In agreement with the apparent difference in cluster age, our results suggest the disk galaxies of Abell 370 have had more time in the cluster environment, relative to the disks in Abell 851, to redden and/or fade into obscurity.

Subject headings: galaxy clusters

1. Introduction

The centers of rich galaxy clusters today are dominated by red, early-type galaxies. The standard picture for the formation of elliptical galaxies (*e.g.*, Eggen, Lynden-Bell, and Sandage 1962; White and Rees 1978) has their stars forming rapidly in a single burst at high redshift and subsequently evolving passively in a generally redward march to their present colors. The color-magnitude relation in ellipticals is attributed to more massive galaxies retaining their star forming gas from ejection by supernovae winds more effectively, resulting in higher metallicities and hence redder colors (Arimoto and Yoshii 1987). The apparent coevality and old age of present-day cluster ellipticals is strongly implied by the small scatter in the colors at a given magnitude, and the similarity of those colors from cluster to cluster (Bower et al. 1992, hereafter B92). This suggests the spectral energy distributions (SEDs) of ellipticals are a function only of their mass and of the time since their formation. A sample of clusters spanning a wide range of redshifts might therefore offer an excellent means of studying galaxy evolution at large lookback time, each cluster providing a “snapshot” of the evolutionary history of early-type galaxies. If the range of formation epochs was small enough, one could even hope to determine the basic cosmological parameters H_0 and q_0 by mapping a range in cluster redshifts to the corresponding time interval derived from changes in the cluster elliptical SEDs, in essence synchronizing the cosmological and stellar evolutionary clocks.

This picture of cluster galaxy evolution was revealed to be overly simplistic with the discovery of a substantial population of blue galaxies in distant clusters, which are largely absent in similar clusters in the present epoch (Butcher and Oemler 1978, 1984). Spectroscopy of these blue cluster galaxies has revealed them to be a diverse population comprising star forming systems, “post-starburst” galaxies and AGN. In most cases, however, the blue colors appear to result from star formation. Recent *HST* imaging

of clusters at $z=0.3$ to 0.5 (Dressler et al. 1994a and 1994b, Couch et al. 1994, Wirth et al. 1994) shows that most blue objects are late-type disk galaxies, which must have disappeared from the cores of rich clusters by today, or have been transformed into another type of galaxy. A variety of mechanisms have been suggested to explain this process, including ram-pressure stripping, tidal disruption, galaxy interactions, and mergers.

Despite this rapid evolution in the blue population, ground-based photometry and spectroscopy and *HST* imaging shows that a red E/S0 population persists in clusters out to large redshifts and still dominates the cores of rich clusters at least to $z \approx 0.5$. The increasing ratio of disk to spheroidal galaxies with cosmic time, however, suggests an evolutionary connection between these populations which would contradict the simple “single starburst & passive evolution” paradigm for elliptical formation. Furthermore, Dressler and Gunn (1983, 1992; hereafter DG92) found that even some of the red galaxies show spectroscopic signs of recent star formation. These “E+A” galaxies appear to have post-starburst spectra resembling early-type galaxies with a strong A-star population superimposed (but no signs of current star formation). These observations suggest consideration of the antithesis of the “synchronized clock” scenario described above, namely that all elliptical galaxies form by mergers in a process which is continuing to the present day. Tracking the evolution of the elliptical population in distant galaxy clusters can not only test the passive evolution scenario, but could help unravel the Butcher–Oemler effect as well.

With this in mind, we have undertaken a program to trace the photometric evolution of large numbers of cluster ellipticals over the widest accessible range of redshift, and hence cosmic epoch. A substantial number of galaxy clusters are known out to $z \approx 1$ (e.g. Gunn, Hoessel and Oke 1986; Couch et al. 1991) and perhaps beyond (e.g. Dickinson et al. 1995), providing sites for studying elliptical galaxy colors over more than half the age of the

universe.

One difficulty with such a program is that the large redshifts of distant clusters move optical passbands into the blue and near-ultraviolet region of the cluster rest frame. Optically selected samples may therefore incorporate a redshift-dependent bias toward star-forming galaxies, which are bright in the rest frame near-UV, possibly distorting conclusions on galaxy evolution. This bias can be minimized by selecting cluster galaxies at near infrared wavelengths. Infrared photometry samples the peak (in F_ν units) of the spectral energy distributions for normal galaxies, measuring luminosities and colors of the old stellar population which dominates the stellar mass. The effects of ongoing or recent star formation on galaxy selection are thus minimized, and the spectral similarity of spirals and ellipticals in the near-IR insures that a relatively uniform and representative distribution of galaxy types will be identified across a wide range of redshifts. Furthermore, observations in the near-IR are relatively immune to the effects of reddening and extinction. These qualities make the near-IR a valuable regime in which to study distant galaxy clusters.

Near-IR observations of moderate redshift clusters have only become technically feasible in recent years. Lilly (1987) used a single-element detector to obtain photometry of 53 galaxies in five clusters at $z \sim 0.45$. He found the 36 optically red galaxies in his sample to be on average ~ 0.1 mag *redder* in rest frame $V - H$ than the average elliptical in the Coma cluster. While Lilly modelled this surprising result by incorporating an AGB population in a passively evolving model, more recent spectral synthesis models incorporating AGB stars (Bruzual and Charlot 1993; hereafter BC) predict that single age stellar populations should become monotonically bluer at earlier epochs, and thus fail to explain Lilly’s result.

Aragón-Salamanca, Ellis, and Sharples (1991; hereafter AES) published the first array-based infrared study of galaxy clusters. Based on a sample of 46 cluster members

down to $K = 17.5$ in Abell 370, a rich cluster at $z = 0.374$, they found that the $R - K$ colors lie along a color–magnitude (c–m) relation similar to that observed for present–day ellipticals, but with significant scatter to both the red and the blue. AES interpreted the redward scatter as arising from AGB stars in a post–starburst phase, supporting the idea that most cluster galaxies, including the ellipticals, passed through a starburst phase at some time after formation.

Aragón-Salamanca et al. (1993; hereafter AECC) observed 10 clusters with $0.5 < z < 0.9$ at V, I , and K . In contrast to Lilly and to AES, they found that the optical–IR colors of the reddest cluster galaxies (the “red envelope,” O’Connell (1987)) became progressively bluer towards higher z , in accord with predictions from models for passive evolution of single–age stellar populations. Furthermore, AECC found that clusters at the same redshift showed the same amount of color evolution, supporting the idea of coeval elliptical formation at high redshift. The bluing of the red envelope has also been seen by Rakos and Schombert (1994) in the optical colors of a sample of high redshift clusters, and in spectroscopic measurements of the 4000\AA break amplitude in clusters at $z > 0.6$ by Dressler and Gunn (1990). These results are all broadly consistent with the “synchronized clock” scenario for elliptical galaxies outlined above.

The apparently conflicting data on the red envelope and differing theoretical predictions of the effects of AGB populations suggest that the history of cluster galaxy evolution is by no means settled yet. The advent of new, large–format infrared arrays has opened a new era in which the measurements painstakingly collected by Lilly and by Aragón-Salamanca et al. can be substantially improved in both quantity and quality. The AECC sample of 10 clusters contained only ~ 15 color–selected galaxies per cluster. With larger arrays, we can now observe ~ 100 galaxies per cluster with relative ease in a single observation. In addition, with the possibility for morphological classification of high redshift galaxies from

HST imaging, the field is clearly open to progress.

Infrared array cameras have been used to obtain multi-wavelength imaging photometry for ~ 30 clusters in the redshift range $0 < z < 0.7$. This dataset consists of *JHK* imaging reaching a limit ~ 2 mag below L^* over a ~ 1.5 Mpc diameter field, as well as complementary optical photometry. This paper presents our methods of data reduction, object detection, sample definition, and photometry. The color evolution of the red envelope is investigated in the first two clusters observed in the survey, Abell 370 ($z = 0.374$) and Abell 851 ($z = 0.407$, also known as Cl 0939+47). Future papers will present the larger data set for clusters at both lower and higher redshifts, and investigate the evolution of the galaxy population across a much broader range of cosmic epoch. A cosmology with $q_0 = 0.1$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is assumed throughout this paper, leading to a lookback time of 4.5 Gyr for Abell 370 and 4.8 Gyr for Abell 851. The relative distance modulus between Coma and the two clusters is 6.40 mag for Abell 370 and 6.61 mag for Abell 851 for our adopted cosmology.³

2. Data

Images of galaxy clusters were obtained over a wide wavelength range to enable an empirical approach to studying galaxy evolution. Galaxies with different redshifts can be compared at constant rest frame wavelengths (Figure 1). Furthermore, the relatively unexplored area of infrared galaxy colors at moderate redshifts can be explored.

³Adopting $q_0 = 0.5$ changes the relative distance modulus by approximately -0.15 mag. This is relatively insignificant for the analyses presented here (which primarily concern galaxy colors) because of the shallow slope of the color-magnitude relation.

2.1. Observations

Near-IR imaging was obtained of Abell 370 and Abell 851 using SQIID (Ellis et al. 1993) at the KPNO 1.3m telescope. SQIID uses four PtSi 256×256 arrays fed by a system of dichroic beam-splitters to provide wide-field (~ 5.5 arcmin), simultaneous *JHKL* band imaging capability at 1.30 arcsec per pixel resolution. Data were not saved from the *L* band channel because of the high thermal background. Observations were obtained over the course of three nights in 1991 December, using a two dimensional dither pattern with a 10 arcsecond step size and 30 arcsecond total extent. Approximately 115 five minute frames were obtained in the *JHK* bands for both clusters. Several standard stars from the list of Elias et al. (1982) were observed each night, at 4 separate array positions for each star. In addition, 5 Coma cluster galaxies from Persson et al. (1979) were observed, using a dither pattern with two arcminute steps and separate off-source sky frames. The weather was photometric throughout the time the clusters were observed.

Optical images of Abell 370 and Abell 851 were obtained through intermediate bandwidth filters chosen to approximately match the effective wavelength of the rest frame *V*-band in each cluster (see Figure 1). For Abell 370 the relevant optical band is centered at 7520\AA ($\Delta\lambda = 375\text{\AA}$), and for Abell 851 at 7840\AA ($\Delta\lambda = 325\text{\AA}$). Abell 370 was observed at the KPNO 2.1 m telescope, in photometric weather on 1991 November 2, with the T2KA chip giving a scale of $0.3\text{ arcsec pixel}^{-1}$. Abell 851 was observed also at the 2.1 m, in photometric weather on 1992 April 4, with the T1KA chip giving a scale of $0.3\text{ arcsec pixel}^{-1}$. Spectrophotometric standard stars were observed to calibrate the imaging.

2.2. Reductions

The IR data were reduced using DIMSUM⁴. The data were first linearized, and then trimmed to exclude masked columns and rows on the edges of the arrays. Due to the highly uniform response of the PtSi arrays, flat-fielding was not performed. Tests of standard star images flattened with dome flats, sky flats, and no flats showed no improvement in the repeatability of measured standard star magnitudes from flatfielding. Sky and dark subtraction were done by subtracting a scaled median of 9 temporally adjacent exposures from each frame. Due to the large number of objects in each field, a first pass reduction was used to produce an object mask for each frame. This was done on the fully stacked mosaic image, and thus the resulting mask excludes objects too faint to be detected on individual exposures as well as bright objects. The data were then rereduced using the object mask to suppress object contamination of the sky in the production of sky frames. Final mosaiced images of each cluster were made with a replication of each pixel by a factor of 4 in both dimensions, eliminating the need for interpolation when the individual frames are co-aligned, while conserving flux. Bad pixels were excluded from the summed images. The resulting FWHM of a stellar image in the summed K band image is ~ 2.3 arcsec.

Reduction of the optical data was done using standard procedures. The optical images were geometrically transformed to match the pixel scale (0.326 arcsec after pixel replication) and orientation of the IR images. A 7520, J , K color composite image of Abell 370 is shown in Figure 4, and a 7840, J , K color composite image of Abell 851 is shown in Figure 5. Henceforth, the 7520 and 7840 filters are referred to as “optical”. Only regions of the final mosaic images with $>99\%$ of the total integration time were used in this investigation, thus insuring that the sky noise remains very nearly uniform across the entire field of view. The resulting fields are ~ 4.7 arcminutes square.

⁴Deep Infrared Mosaicing Software, a package of IRAF scripts, available on request from the authors.

3. Photometry

The SQUID photometry was transformed to the CIT scale by using observations obtained each night of several standard stars from the list of Elias et al. (1982). The standard star solution gave residuals of ± 0.025 mag. The transformation equations to convert from instrumental (jhk) to calibrated (JHK) magnitudes are:

$$J = j + jzp - 0.14 \times (airmass)$$

$$H = h + hzp - 0.06 \times (airmass) - 0.21 \times (H - K)$$

$$K = k + kzp - 0.09 \times (airmass)$$

where hzp, hzp, kzp are the instrumental zeropoints. The H band solution includes a large color term in agreement with the one determined by Silva and Elston (1994).

The optical magnitudes were calibrated onto the AB system (*e.g.* Oke 1979) using spectrophotometric standard stars and then transformed to a “standard” (approximately normalized to α Lyrae) system using $m(7520)_{std} = m(7520)_{AB} - 0.36$, and $m(7840)_{std} = m(7840)_{AB} - 0.37$. In our magnitude system, Vega has $m = 0$ in the JHK bands (Elias et al. 1982) and $m = +0.03$ in the optical bands, as it does in the calibration of the V band by Johnson & Morgan (1953).

3.1. Photometric Tests

An internal check of the K band photometric precision was performed on a sample of ~ 100 galaxies in Abell 370. Photometry in 4.8 arcsec diameter circular apertures was

measured on independent datasets obtained on two different nights. The differences in the measured magnitudes for the same objects are plotted against K mag in Figure 2. Also shown is the expected $\pm 1\sigma$ errorbar at $K = 16.5$ calculated from Poisson statistics, which is only slightly smaller than the actual scatter. The calculated rms magnitude differences indicate that the K photometry in the final, summed images are good to 15% on average down to $K = 18$. This is considerably below the estimated $K^* = 17.0$, which would be measured in the 4.8 arcsec aperture, assuming a present-day value $M^*(K) = -25.1$ (Mobasher et al. 1993) and a k -correction derived from an unevolving BC elliptical model.

Two external tests of the IR photometry were performed. A small number of Coma cluster galaxies were imaged with SQUIID during our 1991 observing run. The resulting photometry from our data is compared in Table 1 with that of Persson et al. (1979). For the 5 galaxies in common with their dataset, the mean differences in magnitudes are: $J = -0.01 \pm 0.03$, $H = -0.01 \pm 0.02$, $K = 0.00 \pm 0.02$. While these galaxies are ~ 6 mag brighter than the galaxies in our distant clusters, the comparison suggests no systematic difficulties with our photometry. Our K magnitudes for Abell 370 have also been compared with those of AES. There are ~ 43 galaxies in common between the two studies. The AES photometry was first converted from the UKIRT system to the CIT system used here (Casali and Hawarden 1992). Magnitudes were measured from our data through the same size apertures used by AES. The differences are plotted against K in Figure 3. A systematic offset is seen in the sense of our measurements being ~ 0.05 mag fainter on average than those of AES. Most of this offset is attributable to the better seeing reported by AES (2.0 arcseconds compared to our 2.3 arcseconds). Using model galaxies with appropriate profiles and sizes (as in §4.1 below), our aperture magnitudes should be ~ 0.03 mag fainter due to the poorer seeing. Thus, the comparison shows reasonable agreement in zeropoint, with a dispersion of 0.15 mag down to $K = 17.5$.

3.2. The Cluster Catalog

Object detection was carried out on the sum of the J , H and K images in order to minimize false detections at the faint end. The IR sum goes significantly deeper than the individual bandpasses. The small range of colors for most objects in the IR images ensures that little or no selection bias is introduced by this procedure, especially since the final galaxy catalogs are truncated to a limiting magnitude $K \sim 18$ where incompleteness first sets in (see below).

Object detection, cataloging, and photometry was done using the FOCAS package (Valdes 1982), with some recent modifications and improvements by Valdes and by the present authors. To understand its operation on our data, FOCAS was run on an simulated cluster image having the noise and object density characteristics of the real K image of Abell 370. Frames were created to simulate the individual exposures in the raw dataset. These raw frames were passed through the reduction procedures described in §2.2. The advantage of the simulated image is that the positions and magnitudes of all galaxies are known. No attempt was made to include galactic stars, foreground or background field galaxies in the artificial images. Experiments with varying the minimum detection area, the detection level, and the spatial filter were performed with the FOCAS object detection routine on the artificial cluster image. The resulting detections at faint magnitudes were inspected visually and compared with the known galaxy list to determine a reliable set of detection parameters.

FOCAS was then used for object detection on the actual cluster data using the sum of the JHK images as described above. The detection parameters were set at the 2.5σ level, with a 9×9 pixel⁵ ($\sim 2''.9 \times 2''.9$) tapered boxcar spatial filter, and a minimum area criterion

⁵When referring to pixels henceforth we will always mean “sub-pixels” of the original

of 50 pixels, which is about $1.3 \times$ the seeing disk area at FWHM. Sky measurement for each object was made using $\pm 2\sigma$ clipping about the mean, a 6 pixel buffer region around the cataloged area of each object and an 8 pixel wide sky region. This ensures that the sky measurement is relatively unbiased by light at large radii from the object under consideration. Splitting of merged objects was done within FOCAS using a reduced minimum area criterion of 25 pixels to better separate overlapping objects. Comparison of the results with the optical images (taken in much better seeing) indicates that the splitting was largely successful in separating merged objects in the infrared data. The resulting catalog was then used to define photometric apertures for objects in all four IR and optical bands. In this way, the same isophotal and sky areas are used for each object in each band. For the remainder of the analysis, the catalog was restricted to a limiting aperture magnitude of $K = 18.0$. The final catalogs contain 162 objects for Abell 370, and 154 for Abell 851.

A test of the FOCAS catalog completeness was made using an artificial cluster image which simulates the sum of the JHK images of Abell 370. In each trial, 10 galaxies at a given magnitude were added at random positions to the artificial image. Only a small number of galaxies was added in each trial so as not to greatly increase the galaxy density, which is an important factor for object detection in a cluster. FOCAS was run on this image and the fraction of the extra galaxies found recorded. Trials were repeated many times with the extra galaxies having $K=16.5, 17.0, 17.5, 18.0, 18.5$, and 19.0 to statistically determine the completeness at these limiting magnitudes. The results are shown in Figure 6. The plot indicates that using our adopted detection parameters produces a catalog of objects that is 90% complete at $K = 18.0$.

image, i.e. the $0''.326$ pixels that result after the 4×4 replication described in §2.1 above.

3.3. Aperture Photometry

A single-size, metric circular aperture was chosen for the photometry because such measurements are easy to reproduce and correction for seeing effects is more straightforward. Apart from signal-to-noise considerations, the main disadvantage of this choice is that single-size apertures measure different fractions of the total light depending on a galaxy’s luminosity, angular size and light profile. The fact that the galaxies of interest are all at the same redshift in each cluster, however, ensures that the aperture corresponds to a fixed metric diameter for all cluster galaxies. Single-size apertures should not adversely affect the calculated colors, as long as the apertures are relatively large, and the effective seeing of the measured images is the same. The seeing for the optical images was ~ 1 arcsec, much better than for the near-IR data. Therefore the optical band images were convolved with a Gaussian to produce an image with a PSF approximately similar to that of the near-IR images. Galaxy crowding can also affect simple aperture magnitudes, but for most objects in these clusters this is relatively unimportant given the adopted aperture sizes. The simplicity of the aperture measurements was judged to outweigh the disadvantages.

Extensive tests of aperture photometry were performed on simulated galaxies of various sizes produced with the IRAF/artdata tasks to quantify single-size circular aperture photometry biases on the measured magnitudes and colors. These galaxies simulated the range of apparent magnitude and size expected for elliptical galaxies in the K and optical band images. Noise characteristics of the Abell 370 images were imposed on the simulated galaxies, which were produced both with no seeing and after being convolved with stellar images taken from the Abell 370 K and optical images. These tests demonstrated that for an aperture diameter about twice the seeing FWHM, errors due to differing PSFs in the optical and K bands are kept below 0.02 mag within the luminosity range of our sample. Color gradient information is preserved in the measured apertures as long as the effective

seeing of the various bands is the same.

Metric aperture diameters of 30 kpc were adopted for the final photometric measurements, corresponding to 4.5 arcsec for Abell 370 and 4.3 arcsec Abell 851. Tables 2 and 3 present the resulting catalogs for Abell 370 and Abell 851, respectively. Column (1) gives an ID number from this paper which is ordered consecutively by K magnitude, and column (2) gives the Butcher–Oemler ID for galaxies in Abell 370 and the Dressler & Gunn ID for galaxies in Abell 851. Columns (3) and (4) give the x, y positions in arcseconds relative to the brightest galaxy (in the K band) in the cluster, which is marked in Figures 4 and 5. The J2000 coordinates of the two brightest galaxies are given in Tables 2 and 3. Column (5) gives the membership status based on published spectroscopy (Abell 370: Mellier *et al.* 1987; Abell 851: DG92), where SM and SNM denote spectroscopic members and nonmembers, respectively. Column (6) gives the morphological classification from *HST* imaging (described below) with E for elliptical, L for S0, A for Sa, B for Sb, C for Sc, D for Sd, and M for merger. Column (6) also shows an asterisk for those objects determined to be stars from their shapes in the *HST* imaging; however this determination is not complete—fainter stars are not necessarily classified as such. Columns (7–9) give the KHJ aperture magnitudes, and column (10) gives the optical– K color. Color–magnitude diagrams for the catalog objects of the two clusters are shown in Figure 7. Errorbars shown at representative K mag indicate the $\pm 1 \sigma$ measurement scatter in the colors determined from a comparison of data obtained on separate nights.

One possible correction to the photometry not discussed yet is galactic extinction. Both Abell 370 ($b = -54^\circ$) and Abell 851 ($b = +48^\circ$) are at relatively high galactic latitude so low values of $E(B - V)$ are expected. From their positions in the maps of Burstein and Heiles (1982), the predicted values are < 0.03 for Abell 370 and ~ 0.0 for Abell 851. Values of $E(B - V)$ of 0.01 for Abell 370 and 0.0 for Abell 851 are adopted. The standard

interstellar extinction curve of Mathis (1990) was used to convert $E(B - V)$ to extinctions in the relevant bandpasses. In the photometry reported in Table 2, no correction has been made for galactic extinction. The extinction correction is made later when making comparisons with models and with the Coma cluster. An uncertainty of 0.02 mag in the optical- K colors due to the uncertainty in the galactic extinction has been assumed in calculating systematic errors for both clusters.

4. Results

4.1. Field Correction

The general distribution of objects in Figure 7 for the two clusters is broadly similar, and resembles that seen in purely optical c-m diagrams of distant clusters (e.g. Butcher, Oemler and Wells 1983; DG92). A sloping ridge line forms a “red envelope” which in nearby clusters is comprised mainly of early-type galaxies. Not all of the objects shown in the c-m diagrams are cluster members; field galaxies contaminate the samples at all magnitudes and colors. Ideally, spectroscopic redshifts would be available for all galaxies in the two fields so that members-only versions of the c-m diagrams could be constructed. Compared to other clusters at similar redshifts, these two have a large number of spectroscopically determined members (48 for Abell 370, Mellier et al. 1987; 26 for Abell 851, DG92). But compared to the total number of galaxies in each field, the fraction of confirmed members is still small. Also, spectroscopically-selected samples may be biased towards bluer galaxies. To make better use of the large number of galaxies in our samples, most of which are expected to be cluster members, a statistical correction can be made for the field galaxy population. Based on the Glazebrook et al. (1994) field galaxy counts in the K band approximately 40 field galaxies should be seen in our ~ 5 arcmin square fields to a limiting magnitude of $K = 18.0$.

The field correction was made in the optical– K vs. K c–m plane to preserve the c–m information under investigation. The details are described here for Abell 370; the procedure for Abell 851 was similar. A composite “field” c–m diagram was first constructed, using field galaxy photometry from Glazebrook et al. (1994) down to $K = 17.25$, where incompleteness sets in, and from McLeod et al. (1994) between $K = 17.25$ and 18. Glazebrook et al. provide RIK for a 552 arcmin² survey, and McLeod gives RIK_s for a 11.9 arcmin² survey. The Glazebrook and McLeod $I - K$ colors were approximately transformed to the observed optical– K color by computing synthetic colors on a variety of BC model spectra at various redshifts and determining the transformation as a function of $R - I$. A composite “field” c–m diagram was constructed from the Glazebrook and McLeod data with the total number of objects scaled to the solid angle of the cluster image. The field c–m diagram was then overlaid on the Abell 370 optical– K c–m diagram, and for each object in the field sample, the nearest cluster object in color–magnitude space was selected and removed. This method is operationally similar to the approach used by Dressler et al. (1994a) to evaluate field contamination probability for Abell 851 (see their figure 1), although they do not actually remove objects from their sample on that basis. It is important to stress that the objects remaining in our “field–corrected” sample are not all expected to be *bona fide* cluster members, but simply have a optical– K vs. K distribution *consistent* with that expected for an actual, complete sample of cluster galaxies.

The field correction resulted in the removal of 38 galaxies from the Abell 370 catalog. An additional 2 galaxies were removed because they are larger and brighter than the two central dominant galaxies yet are located far from the central regions. Finally, 13 stars, as determined from their FWHM sizes in the unblurred optical image or in the WFC image, were removed to complete the field correction. This is somewhat larger than the 9 stars predicted by the K star counts in the Glazebrook et al. survey. The resulting numbers of galaxies in the field–corrected samples are 109 for Abell 370 and 99 for Abell 851. Figure 8

shows the optical- K c-m diagrams for the field-corrected samples of the two clusters.

4.2. Photometric Comparison to the Coma Cluster

The coincidence of our optical and K band data on these $z \sim 0.4$ clusters with the rest frame V and H bands offers the opportunity for direct comparison with the photometric properties of present-day elliptical galaxies. This approach, which was used by Lilly (1987), AES, and AECC, avoids the pitfalls of using large k -corrections or relying solely on comparison with the predictions of spectral synthesis elliptical models. B92 have published $UVJK$ photometry of a sample of ~ 50 E/S0s in the Coma cluster ($z=0.023$); unpublished H photometry was kindly provided by R. Bower.

Before the comparison can be made several corrections and transformations must be applied to the Coma and moderate-redshift cluster photometry to place them on the same footing. The Sandage and Visvanathan (1978) growth curve was used to transform the 12 kpc diameter Coma H photometry to the necessary 30 kpc diameter aperture size. This aperture correction was typically 0.4 mag. Luminosity evolution has not been applied to the Coma photometry. Any reasonable amount of luminosity evolution out to $z \sim 0.4$ would be small and have little effect on the color evolution being measured. A seeing correction has been applied to the K magnitudes of the Abell 370 and Abell 851 galaxies so that the aperture photometry represents the light which would be measured in the metric sizes without dimming due to seeing. This correction was evaluated by comparing aperture photometry on an artificial galaxy before and after convolution with artificial seeing, and amounts to -0.22 mag.

Because the bandpasses employed here do not precisely match the V and H bands at the redshift of Coma, a differential k -correction is needed to transform the Coma

$V - H$ colors to the redshifted optical- K colors. The conversion can be done very accurately because of the close wavelength agreement between the Coma, Abell 370, and Abell 851 bandpasses (*e.g.* Figure 1). The actual transformations are obtained by synthetic photometry using the redshifted standard elliptical model of BC integrated through the appropriate instrument response functions.

Finally, a correction for color gradients was applied to the Coma photometry, because the measurements of the moderate redshift cluster galaxies are made with 30 kpc metric apertures while the B92 photometry of the Coma sample was made with 12 kpc apertures. Values for $\delta(V - K)$ mag per dex in radius between -0.13 and -0.27 have been published (Peletier 1990; Kormendy and Djorgovski 1989; Schombert et al. 1993; Silva and Elston 1994). A gradient of $\delta(V - H) = -0.15$ mag per dex in radius was chosen, assuming the gradient in $H - K$ is very small, resulting in a correction of the Coma $V - H$ colors by 0.06 mag blueward. The color gradient correction at such large radii is uncertain, however, and recent work even calls into question the reality of color gradients outside galaxy centers (Reid et al. 1994). If any, the most likely error made in the color gradient correction is to have made the Coma E/S0s too blue in rest frame $V - H$.

It behooves us at this point to carefully review the sources of error in the comparison of the Coma E/S0s with the moderate- z E/S0s. Random measurement errors have already been discussed in Section 2.2, but systematic errors can be important when trying to ascertain small absolute color differences. The sources of systematic error in the comparison of the optical- K colors with the B92 Coma sample are summarized in Table 4 with their estimated sizes. Adding these in quadrature gives an estimated 0.06 mag of total systematic error.

In Figure 8, the transformed colors from the B92 Coma sample are plotted in the field-corrected optical- K vs. K diagram for the two distant Abell clusters. The transformed

colors are those which would be measured if Coma were observed at $z \approx 0.4$ through the same filters used here. In both clusters, the Coma E/S0 colors form a red border to the moderate-redshift galaxies. The red envelope, which is probably cluster E/S0s, tends to fall somewhat blueward of the mean Coma locus.

4.3. Color Evolution in the E/S0 Populations

Distant clusters have late-type disk galaxies which may affect color comparisons with the Coma E/S0 galaxies. Fortunately, morphological types are now available for large numbers of galaxies in both of the distant clusters thanks to high resolution *HST* imaging. Hubble classifications were kindly provided by A. Oemler (personal communication) based on WFPC images for Abell 370 and WFPC2 images for Abell 851. Within the 2.5 arcmin field of the *HST* images, every galaxy in our IR samples could be assigned a morphological type, so that a subsample derived from cross-correlation of the *HST* data with our near-IR sample essentially remains an IR-selected sample. The resulting IR/HST samples contain 79 objects for Abell 370 and 59 for Abell 851. Within the central 2.5 arcmin of these fields, most objects in the two samples will be cluster galaxies. The field correction for the IR/HST samples described above would predict 9 field objects for Abell 370 and 11 for Abell 851 within the *HST* field of view. Because of this relatively small number of predicted field objects in the IR/HST samples, and due to the difficulty of properly determining a field correction with morphological as well as color and magnitude dimensions, the IR/HST samples will be used without field-correction. These subsamples are plotted in Figure 9 for Abell 370 and Abell 851, again in the optical- K vs. K diagram. To simplify the plots, only a linear fit to the transformed colors of the Coma E/S0s is shown. The morphological types are represented by the various symbols as shown in the plots. The difference between neighboring types in the Hubble sequence is not highly significant, particularly for Abell 370

where classifications were determined from aberrated *HST* images (see also Dressler et al. 1994b). Spectroscopic membership information is included in Figure 9, showing that most of the galaxies are indeed cluster members in the limited areas of the IR/HST samples.

Returning to the color evolution test, in both clusters the E/S0s tend to fall to the blue of the Coma E/S0 line. The median difference in the optical– K between the Coma E/S0 galaxies and the Abell 370 E/S0s is 0.13 ± 0.01 mag, and the same quantity for the Abell 851 E/S0s is 0.18 ± 0.01 mag. The given uncertainties are not dispersions; they are on the medians. These color differences would be similar—0.01 mag smaller—if calculated using field-corrected versions of the IR/HST samples. Statistical tests were performed on the optical– K colors of the Coma vs. moderate- z E/S0 samples. The Kolmogorov–Smirnov test shows that the probability that the Abell 370 E/S0s are drawn from the same parent population as the Coma E/S0s is 4%, while the probability for Abell 851 is 0.01%. The K–S test suggests that there are formally significant color differences between the Coma E/S0 galaxies and those in Abell 370 and in Abell 851. However, systematic error is ignored by the K–S test. After taking into account the systematic error, the color differences for E/S0 galaxies in the two distant clusters relative to Coma are significant at only the 2σ level for Abell 370, and at the 3σ level for Abell 851.

The standard deviation of the optical– K color residuals (the colors of the cluster galaxies minus the corresponding value of the Coma E/S0 fit at the same magnitude) was calculated to be 0.15 mag for both clusters over the entire IR/HST E/S0 samples. The rms scatter in optical– K colors expected from random measurement errors alone is estimated to be 0.11 mag, based on an average over the appropriate magnitude range in Figure 2 (errors in the K magnitude dominate the observational scatter in the optical– K color). By using the color residuals inflation of the scatter due to the c–m relation is avoided. Because the ellipticals tend to be relatively bright, a better estimator of the scatter is obtained by only

considering galaxies with $K < 17$. Down to this limit the rms scatter due to measurement error is 0.06 mag in the optical– K color, while the standard deviation of the optical– K color residuals for the E/S0s is 0.085 for Abell 370 and 0.086 for Abell 851. Thus, the component of intrinsic scatter in the optical– K color of the moderate– z E/S0s brighter than L^* is 0.06 mag for both clusters. The relatively small intrinsic scatter for the two moderate– z clusters is similar to the 0.05 component of intrinsic scatter found by B92 in $V - K$ for their Coma E/S0 sample.

4.4. Morphology and Color

The morphological classes in the c–m diagrams have similar color distributions within each cluster. The median optical– K color residuals for each Hubble type are given in Table 5, which demonstrates the remarkable weakness of the color–morphology dependence for galaxies ranging from ellipticals to types as late as Sc. Note that the *magnitude* of the bluing of the late–type galaxies in Table 5 does not necessarily represent an appropriate measure of passive evolution. To that end, a comparison would have to be made with a sample of *late*–type galaxies from the Coma cluster. The Coma zeropointing is employed to remove the c–m relation, and to enable meaningful color comparisons between the two $z \sim 0.4$ clusters. The weak trend with morphological type seen in Table 5 is similar to the results given by Aaronson (1978) for a sample of nearby field galaxies, and by Bershadsky (1994) for a $z = 0.1 - 0.3$ field sample. Apparently, even the fairly substantial star–forming activity found in Sc galaxies has little effect on their spectra longward of $\sim 0.5 \mu\text{m}$. Unfortunately, no published optical– K colors exist on a suitable sample in a present–epoch cluster for the more direct comparison of our data. Aaronson (1978) observes that the Sc galaxies in his nearby field sample are ~ 0.3 mag bluer in $V - K$ than the E/S0s. The color difference between late–types and early–types in nearby clusters is even less in an optical color

(Oemler 1992), and probably in an optical–IR color too. The bluing trend with galaxy type is nearly absent for Abell 370, while in Abell 851 the amplitude of the trend is similar to that seen in field galaxy populations. As for the measured dispersion, the E/S0s are similar in the two clusters, but the late-type galaxies show wider variation in Abell 851. The result is that the overall scatter (averaged over the entire IR/HST samples) is slightly larger in Abell 851 (0.21 mag) than for Abell 370 (0.18 mag). The implications of the differences and similarities of the color distributions among the Hubble types and between the two clusters will be taken up below.

4.5. Theoretical Models

The passively-evolving elliptical spectral synthesis model of BC provides a moderately good fit to the broadband *UVJHK* colors of an L^* present-epoch elliptical in the Coma cluster (B92). So it is of interest to compare the BC models to the SED of an average L^* E/S0 in the two distant cluster samples. To make the comparison shown in Figure 10, the slope of the c–m relation was used to correct the colors of all morphologically classified E/S0s with $L > L^*$ (where random errors are small) to their equivalent colors at L^* . These colors were averaged to produce a representative early-type SED for each cluster, which was then adjusted for the effect of color gradients from the measured aperture of 30 kpc to 10 kpc, appropriate for comparison to the BC model. The results are plotted in the rest frame in Figure 10, normalized to the observed K -band flux point (i.e. approximately at rest frame $1.6 \mu\text{m}$), and with 1σ scatter bars shown. Similar average E/S0 colors for the B92 Coma sample are also plotted for comparison. The solid line spectrum shows the no-evolution BC elliptical model. The dashed line shows the BC passive-evolution elliptical model for Abell 370, a single-burst model with an age of 9.0 Gyr. The passive evolution

model for Abell 851, which would be similar at all rest wavelengths to the Abell 370 passive evolution model, was omitted from the plot for clarity.

The bluer optical–IR color of the passive evolution BC model compared to the Coma colors provide a better match to the observed data for Abell 851 than for Abell 370. The rest frame ~ 0.9 and $\sim 1.2 \mu\text{m}$ fluxes of the distant E/S0s are not well fitted by the no–evolution model, and are significantly brighter at rest frame $\sim 1.2 \mu\text{m}$ than the Coma E/S0s. The Abell 851 E/S0s are fitted by the passive–evolution model at rest frame $\sim 1.2 \mu\text{m}$. Both $z \sim 0.4$ clusters are fainter than both models at rest frame $\sim 0.9 \mu\text{m}$. It is worth recalling that SQUID obtains *simultaneous* J , H and K measurements, thus minimizing possible sources of systematic uncertainty in color measurements, *e.g.*, those from differences in atmospheric transparency or seeing. The same does not apply to the optical–IR colors.

The infrared color mismatch is seen throughout the luminosity range spanned by our data. Figure 11 compares the $H - K$ c–m diagrams for the IR/HST samples to the average relation for Coma E/S0s. A similar diagram cannot be made for the $J - K$ color because of a lack of Coma data at the rest frame $\sim 0.9 \mu\text{m}$ sampled by the observed J band in the moderate redshift clusters. Instead, Figure 12 shows the $J - K$ c–m diagrams with the BC no–evolution and passive–evolution model colors plotted. No c–m information is involved in the model colors in Figure 12 which are most appropriate at $K^* \sim 17$. However, the near–IR c–m relation is shallow so the comparison of the plotted model colors over the entire magnitude range of the samples is reasonable.

5. Discussion

5.1. The Early–Type Galaxies

5.1.1. Color-Magnitude Relationship

The well-known c–m relationship seen in nearby galaxy clusters is also apparent in the optical– K colors of the galaxies in our two moderate redshift clusters. The slopes for the E/S0 galaxies in the optical– K color are 0.05 ± 0.02 and 0.07 ± 0.01 mag per mag for Abell 851 and Abell 370, respectively. These slopes are determined from linear fits to the colors of the IR/HST samples, with one bright, blue galaxy excluded in each cluster because of their unwarranted effect on the weighting of the fitting. In Abell 851 the excluded galaxy is a known spectroscopic nonmember. Both slopes are similar to the 0.07 ± 0.01 mag per mag of the transformed Coma galaxies. The lack of a slope change between the present epoch and $z \sim 0.4$ is not too surprising. Spectral synthesis models which incorporate metallicity suggest that the slope, which is thought to be due to metallicity variation with luminosity, will change perceptibly only at lookback times exceeding 7–8 Gyr (Arimoto and Yoshii 1987). So testing such a model prediction must await analysis of higher redshift clusters in our sample.

5.1.2. Optical–IR Color Evolution

The c–m diagrams shown in Figures 8 indicate that the reddest galaxies in these two clusters at $z \approx 0.4$ have slightly bluer optical– K colors than do early-type galaxies in the Coma cluster. Morphological classifications from *HST* confirm this result for subsamples of galaxies specifically chosen to have E/S0 Hubble types. Assuming the disk galaxies in Abell 370 and Abell 851 have current star formation typical of spirals in the present epoch, the relatively weak dependence of optical– K color on Hubble type (Table 5) strongly suggests that the observed bluing in the moderate redshift E/S0s is *not* primarily the result

of ongoing or recent star formation, but instead reflects the passive evolution of the old stellar population which dominates the light in the rest frame 0.55–1.6 μm spectral range. Moreover, none of the E/S0s in Abell 851 (DG92), and only 2 (of 52) of the E/S0 galaxies in Abell 370 show signs of recent star formation (*e.g.*, strong Balmer line absorption) in optical spectra (Couch et al. 1994).

The color difference between galaxies in the distant clusters and Coma is small, and in the case of Abell 370 may not be significant given the amplitude of our systematic errors. Even if the bluing trends are not strictly significant with respect to the present epoch, it is clear that the moderate redshift E/S0s are *not* redder, in disagreement with observations by Lilly (1987) and AES. The contradiction probably results from increased data quality afforded by modern detectors, increased sample size, and better present epoch comparison data of B92. Our results also do not agree with those presented by Rakos and Schombert (1994) showing evidence of an AGB effect at $z \sim 0.4$ based on a comparison of the optical colors of a sample of high redshift clusters with the models of Guiderdoni and Rocca-Volmerange (1987). The redder optical colors of the AGB effect should be even more evident in our optical– K colors; however, no such effect is predicted by the BC models. The slightly bluer optical– K colors of the $z \sim 0.4$ clusters are fairly well matched by simple models of passive spectral evolution, and agree with the trend seen by AECC for the bluing of the red envelope in clusters at $z > 0.5$.

Before comparing the optical– K colors between the two $z \sim 0.4$ clusters, it is of interest to compare the global properties of Abell 370 and Abell 851. The optical and x-ray morphologies of the two clusters exhibit striking differences. The galaxy distribution of Abell 370 is centrally concentrated and relatively symmetric. Its two dominant galaxies are reminiscent of the configuration seen in the Coma cluster. The x-ray morphology as observed by the Rosat HRI (Mellier and Bohringer 1994) is bimodal with peaks associated

with each of the two dominant galaxies, but is otherwise fairly round and centrally peaked. The presence of the famous giant luminous arc, faintly present in our IR images, strongly argues for a sharply concentrated central mass distribution (Grossman and Narayan 1989; Wu and Hammer 1993). The galaxy distribution of Abell 851, by contrast, is more clumpy and irregular. Wide-field optical images show several apparently rich subclusters situated at large radii, plausibly still infalling toward the central cluster (Dressler et al. 1994a; D. Silva, personal communication). Rosat PSPC observations by Porter (1994) tell the story most strikingly. While quite x-ray luminous, the cluster is large and highly irregular, with several clear sub-clumps visible, and a low average surface brightness lacking the strong central concentration seen *e.g.* in Coma or Abell 370. The visual impression, evident in our images, that Abell 370 is richer than Abell 851 is somewhat misleading. A good case can be made that Abell 851 is dynamically younger than Abell 370, and is being viewed at an earlier stage in its formation.

Bearing the foregoing discussion in mind, it is of interest that the optical- K colors of early-type galaxies in Abell 851 are 0.05 mag bluer than those in Abell 370. The passive evolution model of BC predicts a difference of 0.02 mag in the optical- K color due to the difference in cosmic time between the two redshifts (only ~ 0.3 Gyr for $H_0=50 \text{ km s}^{-1} \text{ Mpc}^{-1}$). The significance of the resulting 0.03 mag difference is tempered by the systematic error, although many of the sources of uncertainty given in Table 4 cancel out for a comparison only at $z \sim 0.4$. If real, the optical- K color difference could be due to younger ages for the early-type galaxies in Abell 851. Taken at face value, this could imply non-coeval histories for the elliptical galaxy populations in the three clusters, either due to different formation redshifts or to important differences in their recent star formation histories. Here, “recent” means long enough ago so that evidence of star formation is no longer seen in the optical spectra of the cluster E/S0s. Given the small amplitude of the observed effect, the suggested non-coeval formation cannot be considered a firm result from

the present data.

5.1.3. *The History of the Stellar Populations*

The intrinsic scatter found in the optical– K colors of E/S0s in the two moderate redshift clusters offers a means of placing limits on the galaxies’ stellar population history. Considering the scatter at a given magnitude largely avoids the complications due to the age–metallicity degeneracy. The scatter in the colors could result from several factors, including the age of the formation epoch, the duration of the formation epoch, and recent starburst activity. The latter factor is particularly of interest with respect to understanding the Butcher–Oemler effect.

Along with the Bruzual (1983) models, B92 used the intrinsic component of the scatter in the Coma E/S0 $U - V$ colors to place limits on the age and coevality of the formation epoch. They found that the Coma E/S0s must have formed at least 13 Gyr ago (for $q_0=0.1$) if the formation process lasted on the order of the galaxy collapse timescale of ~ 1 gyr. These results are in rough agreement with those of Rakos and Schombert (1994) for the formation epoch of the red population in a sample of high redshift clusters. Based on passive evolution model fits to their optical colors, Rakos and Schombert (1994) put the age of the early–type population at greater than 15 Gyr. B92 also explored limits on the role of recent starbursts, specifically with an eye towards Butcher–Oemler galaxies at moderate redshifts. They concluded that the intrinsic scatter in the Coma E/S0s $U - V$ colors allowed for no greater than 10% by mass starbursts in the early–type populations at $z \sim 0.5$.

The fact that the intrinsic scatter in the optical– K colors of the E/S0 populations in Abell 370 and Abell 851 is not significantly greater than that seen by B92 for a similar color on their Coma E/S0 sample suggests that there has been little starburst activity in the star

formation history of cluster early-type galaxies since $z \sim 0.4$. This argument assumes that the moderate redshift E/S0s in our samples evolve into the corresponding Coma population. But, it is difficult to use our optical- K colors to place interesting limits on starbursts at $z > 0.4$ because they are relatively insensitive to the effects of recent star formation (*e.g.*, Aaronson 1978), unlike the $U - V$ colors used by B92 for this purpose. Only very recent starbursts, on the order of a few $\times 10^8$ years, can be ruled out as having caused the scatter in the intrinsic optical- K colors of the E/S0s in Abell 370 and Abell 851.

Our optical- K colors *can* be used with the BC models to calculate interesting limits on the epoch and coevality of early-type galaxy formation under the assumption of passive evolution in the original stellar populations. If a Salpeter IMF with mass limits of 0.1 M_\odot and 125 M_\odot and a 1 Gyr burst are assumed in computing a BC elliptical model, then the E/S0s must have formed at least 5 Gyr prior to the cosmic time at $z \sim 0.4$ if the spread in the formation time of the individual ellipticals was ~ 1 Gyr. Decreasing the formation spread time to 0.5 Gyr allows the minimum formation time to be only 4 Gyr prior to $z \sim 0.4$. It is important to note that these formation epoch limits are *only* based on the observed scatter, and that they ignore the absolute colors. Any age less than about 5 Gyr at $z \sim 0.4$ would give unacceptably blue optical- K colors compared to the observed E/S0 colors in Abell 370 and Abell 851. Increasing the formation spread time to 2 Gyr would force the formation epoch to be at least 7 Gyr prior to the cosmic time at $z \sim 0.4$. The BC passive evolution model which roughly fits the observed optical- K colors of the IR/HST samples' E/S0s gives a present epoch galaxy age of 13.5 Gyr with our adopted cosmology. The lower limit of 10 Gyr to the present age of the E/S0s in Abell 370 and Abell 851 based on the optical- K scatter approximately agrees with the age of our passive BC model. Qualitatively, the small scatter in the $z \sim 0.4$ optical- K colors agrees with the result of AECC that the early-type galaxies in $z > 0.5$ clusters formed at the same time at high redshift.

5.1.4. *The IR Colors*

The curious departures of the other infrared flux points for the two $z \sim 0.4$ clusters from the model caution against overinterpretation of comparisons with existing evolutionary synthesis models like those of BC—other effects such as metallicity may play an important and as yet unquantified role. The rest frame $\sim 1.2 \mu\text{m}$ flux density of the Abell 370 E/S0s deviates further from the model than that for Abell 851, while the opposite is the case at rest frame $\sim 0.9 \mu\text{m}$. These differences cannot be explained by standard passive evolution, nor by starbursts. The B92 sample does not provide a check on the BC model at rest frame $\sim 0.9 \mu\text{m}$, so one may only wonder if the model provides a good fit to present epoch galaxies at these wavelengths. At rest frame $\sim 1.2 \mu\text{m}$ the Coma E/S0s are actually fainter than the models so that the moderate redshift E/S0s are even more discrepant relative to our “empirical” model of the present epoch.

This spectral region is poorly understood for present epoch galaxies and could be subject to metallicity effects during stellar evolution in galaxies. Some relevant work has been done by Frogel, Terndrup and collaborators on the colors of Galactic bulge M giants, which probably dominate the stellar light redward of $1 \mu\text{m}$ in elliptical galaxies. Frogel et al. (1990) found the unusual property that the $J - H$ colors of M giants get bluer with increasing metallicity for stars of similar temperature. They attribute the effect to a decrease in the size of the H band bump in the bulge giants, which may be linked to their greater metallicity. Increased H_2O absorption in the metal-rich bulge giants was originally proposed by Frogel and Whitford (1987) as the explanation. The greater steam absorption would make up for the opacity minimum of the H^- ion at $1.6 \mu\text{m}$ which causes the H band bump. However, subsequent work by Terndrup, Frogel, and Whitford (1991) does not support this conclusion. Terndrup et al. (1990) suggest that synthesis models of ellipticals should use bulge M giants instead of the solar neighborhood spectra used in *e.g.* the BC

models. The effect on the models plotted in Figure 10 probably would be to make the rest frame $1.2\ \mu\text{m}$ – $1.6\ \mu\text{m}$ color bluer and thus more closely match the $z \sim 0.4$ E/S0s.

However, a bulge–giant BC model would fit the B92 Coma sample worse at these wavelengths. The present epoch BC model with local M giant spectra is already bluer at rest frame $1.2\ \mu\text{m}$ – $1.6\ \mu\text{m}$ by about 0.05 mag than the B92 E/S0s. Using the even bluer bulge M giant spectra would increase the discrepancy at these wavelengths. It would also make the rest frame $V - H$ comparison of the BC model with B92 worse in the sense of the model being too blue. One way out of this latter problem would be to use an older model. For example, a BC model with a present age of 15 Gyr would be redder in rest $V - H$ than the 13.5 Gyr model used in this paper so presumably would fit the B92 colors if bulge M giants, which do not affect the rest V band light, were used in place of the solar neighborhood M giants. The effect of using an older, bulge–M–giant BC model on the optical-IR comparison with the $z \sim 0.4$ E/S0s would be only a small change; the bulge giants act to decrease the IR light while the older age acts to increase the IR light. The probable result is that the Abell 370 and Abell 851 E/S0s would still be fit by the passive evolution BC model.

In the scenario described above, another consideration is the way the models are brighter at rest frame $\sim 0.9\ \mu\text{m}$ than our moderate redshift clusters. Frogel et al. (1990) also find that TiO absorption around 0.8 – $0.9\ \mu\text{m}$ is stronger in bulge M giants compared to local giants. So if bulge M giants were substituted for their solar neighborhood counterparts in the BC stellar spectra library the result should be a decrease in flux in the BC elliptical model around 0.8 – $0.9\ \mu\text{m}$, which would better fit the $z \sim 0.4$ E/S0s.

The discussion above is only qualitative but it does suggest that the unexpected colors of the moderate redshift E/S0s between rest frame $\sim 0.9\ \mu\text{m}$ and $\sim 1.2\ \mu\text{m}$ might be related to metallicity effects. Current work on the isochrone synthesis technique includes expanding

the input spectra and stellar evolutionary tracks to include non-solar metallicities, so that in the future the above speculation may be tested (Charlot, personal communication). Perhaps the most worrisome issue is the implied metallicity differences between the Coma and moderate redshift E/S0s. Terndrup et al. (1990) find that $\Delta[\text{Fe}/\text{H}]=0.3$ between the solar neighborhood and bulge M giants. The implication is that the metallicity of the $z \sim 0.4$ E/S0s would have to change by this amount if they are to become their Coma equivalents by the present epoch. An interesting observation to obtain with regard to this scenario would be rest frame K band imaging of the $z \sim 0.4$ clusters. Besides the variation of the $J - H$ color with metallicity, Frogel et al. (1990) find that $H - K$ gets redder with increasing metallicity for M giants. Though technically difficult, observations of moderate redshift clusters in the L band, which samples the rest frame K , is becoming feasible for $L > L^*$ galaxies.

5.2. The Late-Type Galaxies and the Butcher-Oemler Effect

The optical- K colors of galaxies in Abell 851 have a somewhat larger scatter than do those in Abell 370 (see Figures 8 and 9). Inspecting the distribution by morphological type in the IR/HST sample, it appears that much of this difference is attributable to a population of late-type galaxies in Abell 851 that are both relatively more numerous and bluer than those in Abell 370. Within the *HST* field of view, spirals comprise 46% of the IR/HST sample of galaxies in Abell 851 and 34% of those in Abell 370. Late-type (Sc/Sd) spirals amount to 12% of the Abell 851 population compared to only 4% for Abell 370. Moreover, the Abell 851 disk systems are significantly bluer (~ 0.2 mag for all spiral types) than those in Abell 370 (Table 5). Although not directly quantifiable in terms of the classical Butcher-Oemler fraction, the differences in the spiral populations suggest a stronger Butcher-Oemler effect in Abell 851. This result is in rough agreement with the

classical B–O fractions for the two clusters, $f_B \sim 0.2$ for Abell 370 and $f_B \sim 0.3$ for Abell 851 (Butcher and Oemler 1984; DG92).

The tendency for spirals in present–day rich clusters to be redder than those in the field or in poorer groups has been noted previously (*e.g.*, Oemler 1992). On average, spirals in Abell 370 have optical– K colors little different from those of the early–type galaxies. Similar results are seen for the average $B - V$ colors of nearby cluster galaxies tabulated by Oemler (1992). But at $z \sim 0.4$ the richer environment, Abell 851, has the bluer spiral colors. This difference from the present epoch could correlate either with total system richness or with the dynamical maturity of the clusters. Comparisons with dynamically immature rich clusters and with dynamically mature poor clusters at moderate–redshifts might solve the ambiguity. Photometric data in the same optical–IR system on field spirals at $z \sim 0.4$ also would be valuable for judging whether it is the Abell 851 disks that are bluer than is to be expected for a rich cluster at moderate redshifts, or the Abell 370 spirals that are too red. From the perspective of present epoch clusters, the Abell 851 spirals are too blue. Dressler et al. (1994a) find that most galaxies in Abell 851 have rest frame $B - V$ colors consistent with those of present–epoch field galaxies with comparable Hubble types, with the exception of a tail of faint Sd/Irr galaxies bluer than their present–day field counterparts. (The latter are too faint to be in our IR/HST samples.) Moreover, they see little evidence that interactions and mergers induce bluer colors in the galaxies involved. These results suggest that the Abell 851 spirals are too blue for a rich cluster.

Taken together, these points suggest a “thumbnail sketch” in which the presence of a bluer, more numerous spiral population in Abell 851 correlates mainly with a younger dynamical age. The disk galaxies, which have colors more similar to field disks than to cluster disks, may be falling into Abell 851 from the field or from within loose groups for the first time. In this scenario, the processes which transform the blue, disk galaxy population

in rich clusters would have had more time to operate in Abell 370. Star formation has slowed in the Abell 370 disk galaxies, leaving them to evolve toward redder colors. It may even be that this mechanism disrupts or removes disk galaxies, reducing their specific frequency. The smaller spiral fraction in Abell 370 is consistent with requiring such a mechanism, but statistics based on only two clusters (so far) cannot be considered as conclusive. Infrared selection is particularly valuable for investigating this sort of question, since it minimizes the possibility of bias toward star forming objects when tallying galaxies as a function of morphology or color.

From the present data, we cannot unambiguously determine whether evolution in the Butcher–Oemler “blue population” (mostly disk galaxies) is related to or independent of the properties of the red envelope E/S0s, but the evidence for such a connection is not conspicuous. A clear difference in the colors of the E/S0 population between the two clusters would strongly suggest a connection between the evolution of disk and elliptical galaxies, such as would be expected if the spiral population merged to form ellipticals. But the ellipticals in Abell 851 have only marginally bluer optical–IR colors than those in Abell 370, and the colors in both clusters are essentially consistent with simple passive evolution. There appear to be greater differences in the IR colors between the two $z \approx 0.4$ clusters, but the poor match to the IR colors of Coma galaxies and to the model spectra remains unexplained, leaving us unable to draw any clear inference from this effect. The lack of evidence in support of the merger hypothesis is in agreement with the view of Charlot and Silk (1994) based on their theoretical expectations for $z \sim 0.4$ cluster populations. Our findings could also be in agreement with the result of Bothun and Gregg (1990) that the blue B–O galaxies are S0s undergoing recent star formation at moderate redshifts.

6. Summary

Although they are both rich clusters with similar lookback times, X-ray maps and large-field optical images indicate that Abell 370 is a more evolved cluster than is Abell 851, in the sense of showing a more relaxed distribution of galaxies and hot gas. The greater maturity appears to be reflected in a more highly evolved population of disk galaxies in Abell 370. Our infrared selected samples show that the disk galaxies in Abell 851 are bluer than those in Abell 370, and represent a greater fraction of the total sample, suggesting that the disk galaxies in Abell 370 have had more time to redden and/or fade into obscurity. Nevertheless, the early-type galaxies in our samples lend support to the “single starburst at high redshift & passive evolution” paradigm for elliptical formation, and do not seem to be much affected by the differences between the two clusters. The E/S0s in both clusters show a clear color-magnitude relation with a slope and intrinsic scatter similar to that seen in present-epoch Coma E/S0s, indicating that the early-type galaxies within each cluster formed at the same time at an early epoch. The E/S0s in Abell 370 and 851 are slightly bluer in optical- K than those in Coma, by an amount consistent with passive evolution models for elliptical galaxies formed at high redshift (BC). However, the IR colors of an average L^* E/S0 in both clusters differ from Coma E/S0s and from elliptical models in ways that are difficult to explain in terms of age or metallicity effects.

The analysis described in this paper suggests the ways high quality optical-IR photometric observations can be used to quantify the evolutionary histories of cluster ellipticals. In particular, our data on clusters at higher redshifts still to be analyzed will be especially interesting, since spectral evolution is expected to increase the closer one approaches the era (or eras) of galaxy formation. Future papers will address these issues in light of the bulk of our dataset spanning the redshift range up to $z \sim 1$.

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Fig. 1.— A plot of the standard rest frame V , H filters, and the observed 7520, K filters used on Abell 370 in this study. The observed K band shifts to the rest frame H band, and the observed 7520 band shifts to rest frame V .

Fig. 2.— Comparison of K photometry for the same objects measured on two different nights for Abell 370. A theoretical $\pm 1 \sigma$ errorbar is shown at $K = 16.5$.

Fig. 3.— Comparison of K photometry for the same objects in Abell 370 as measured by AES and in this paper. The dashed line marks a linear fit to the differences for $K < 17.5$.

Fig. 4.— Abell 370 7520, J , K composite image, where the colors are set to be 7520=blue, J =green, K =red. The field size is $\sim 4.7 \times 4.7$ arcminutes. The scale in arcsec is shown on the axes with the zeropoints as defined in Table 2.

Fig. 5.— Abell 851 7840, J , K composite image, where the colors are set to be 7840=blue, J =green, K =red. The field size is $\sim 4.7 \times 4.7$ arcminutes. The scale in arcsec is shown on the axes with the zeropoints as defined in Table 3.

Fig. 6.— Sample completeness versus K magnitude calculated from simulated cluster data.

Fig. 7.— Abell 370 (a) and Abell 851 (b), color–magnitude diagrams for the complete IR samples. Symbols denote spectroscopic membership information taken from Soucail et al. (1988) for Abell 370, and from Dressler and Gunn (1992) for Abell 851: solid squares are members, open circles are nonmembers, and open triangles do not have redshifts.

Fig. 8.— Abell 370 (a) and Abell 851 (b), field–corrected optical– K vs. K diagrams, shown together with the appropriately transformed Coma E/S0 sample. Typical $\pm 1\sigma$ errorbars are shown at representative magnitudes. The K magnitudes in this and all subsequent c–m diagrams have been corrected by -0.22 mag for seeing.

Fig. 9.— IR/HST samples for Abell 370 (a) and Abell 851 (b) plotted in optical– K vs. K diagrams with morphology and membership indicated by different symbols. The open symbols have no spectroscopic information. Typical $\pm 1\sigma$ errorbars are shown at representative magnitudes. The best-fit to the B92 Coma E/S0 colors is shown as the heavy line.

Fig. 10.— SEDs of the average elliptical galaxies brighter than L^* in Abell 370 and in Abell 851 (after correction for the color-luminosity relation) relative to the no–evolution and passive–evolution elliptical models of BC represented by the solid and dashed lines, respectively. The average SED of the E/S0s from the Bower Coma sample are plotted as inverted open triangles. The vertical error bars on the cluster points represent $\pm 1\sigma$ scatter, and the horizontal bars represent the FWHM of the filters. The $\pm 1\sigma$ errors on the median colors are roughly the size of the points for all the clusters.

Fig. 11.— $H - K$ vs. K diagrams for Abell 370 (a) and Abell 851 (b) IR/HST samples. Symbols as in Figure 9. Typical $\pm 1\sigma$ errorbars are shown at representative magnitudes. The best-fit to the B92 Coma E/S0 colors is shown as the heavy line.

Fig. 12.— $J - K$ vs. K diagrams for Abell 370 (a) and Abell 851 (b) IR/HST samples. Symbols as in Figure 9. Typical $\pm 1\sigma$ errorbars are shown at representative magnitudes. The no–evolution and passive evolution BC models shown as dashed lines are marked by NE and PE, respectively. The models are appropriate only for an L^* elliptical; the dashed lines do *not* indicate a model c–m relation.

TABLE 1
COMPARISON OF COMA PHOTOMETRY^a

| Galaxy | J(PFA) | J(SED) | H(PFA) | H(SED) | K(PFA) | K(SED) |
|---------|--------|--------|--------|--------|--------|--------|
| NGC4883 | 12.52 | 12.53 | 11.82 | 11.84 | 11.56 | 11.57 |
| NGC4886 | 12.65 | 12.63 | 11.94 | 11.93 | 11.70 | 11.73 |
| NGC4889 | 11.03 | 10.97 | 10.28 | 10.26 | 9.99 | 9.98 |
| IC4011 | 13.27 | 13.26 | 12.61 | 12.57 | 12.32 | 12.32 |
| IC4021 | 12.89 | 12.90 | 12.17 | 12.18 | 11.94 | 11.91 |

^aPFA is Persson et al. (1979), and SED is this paper.

TABLE 2
ABELL 370 PHOTOMETRY

| SED | BO | x(") | y(") | M | Type | K | H | J | 7512-K |
|-----------------|-----|--------|--------|-----|------|-------|-------|-------|--------|
| 18 | ... | 91.6 | 19.6 | ... | * | 10.97 | 11.03 | 11.55 | 2.10 |
| 19 | ... | -47.3 | -51.5 | ... | * | 12.57 | 12.60 | 12.91 | 1.06 |
| 20 | ... | 25.4 | 102.0 | ... | ... | 12.81 | 13.09 | 13.83 | 2.40 |
| 21 | ... | 100.1 | 136.9 | ... | * | 14.19 | 14.34 | 14.95 | 1.62 |
| 22 | ... | -120.0 | 19.2 | ... | * | 15.05 | 15.06 | 15.32 | 0.67 |
| 23 ^a | 10 | 0.0 | 0.0 | SM | E | 15.12 | 15.73 | 16.65 | 3.08 |
| 24 | 6 | 10.1 | 58.4 | ... | E | 15.18 | 15.56 | 16.30 | 2.41 |
| 25 | 9 | 6.5 | -35.5 | SM | E | 15.20 | 15.82 | 16.72 | 2.98 |
| 26 | 14 | -121.9 | 65.9 | SM | ... | 15.26 | 15.89 | 16.76 | 2.99 |
| 27 | ... | 65.2 | 62.6 | ... | ... | 15.67 | 15.86 | 16.49 | 2.28 |
| 28 | ... | -112.5 | 90.3 | ... | ... | 15.68 | 16.25 | 17.11 | 2.86 |
| 29 | 31 | 62.6 | 77.6 | SM | ... | 15.69 | 16.39 | 17.32 | 3.15 |
| 30 | 15 | -61.6 | 36.2 | SNM | ... | 15.71 | 16.26 | 17.08 | 2.77 |
| 31 | ... | 52.8 | -9.1 | SM | E | 15.73 | 16.37 | 17.26 | 3.00 |
| 32 | 29 | -19.9 | -31.9 | ... | L | 15.77 | 16.41 | 17.34 | 3.01 |
| 33 | 22 | 76.3 | 73.7 | SM | ... | 15.78 | 16.36 | 17.29 | 2.94 |
| 34 | 21 | -57.0 | -15.0 | SM | L | 15.81 | 16.39 | 17.28 | 2.95 |
| 35 | ... | 135.3 | 30.6 | ... | ... | 15.82 | 16.02 | 16.64 | 2.21 |
| 36 | 34 | -27.4 | 24.5 | SM | L | 15.85 | 16.48 | 17.36 | 3.05 |
| 37 | 26 | 37.2 | 13.4 | SM | E | 15.86 | 16.49 | 17.40 | 3.05 |
| 38 | ... | -112.5 | 110.2 | ... | ... | 15.86 | 16.22 | 16.90 | 2.28 |
| 39 | 24 | -3.6 | 35.2 | SM | E | 15.88 | 16.53 | 17.40 | 2.99 |
| 40 | 36 | 77.3 | -79.2 | SM | ... | 15.92 | 16.55 | 17.49 | 3.01 |
| 41 | 32 | 120.3 | -51.8 | SM | ... | 15.97 | 16.60 | 17.54 | 2.98 |
| 42 | 58 | -1.0 | -5.9 | SNM | L | 15.98 | 16.60 | 17.49 | 3.20 |
| 43 | ... | 73.0 | 20.9 | SNM | * | 16.04 | 16.10 | 16.53 | 1.16 |
| 44 | 41 | 44.3 | 0.0 | SM | L | 16.08 | 16.72 | 17.64 | 3.06 |
| 45 | 20 | 2.6 | -86.7 | SNM | * | 16.11 | 16.35 | 16.91 | 2.50 |
| 46 | 43 | 27.1 | 23.1 | SM | E | 16.11 | 16.68 | 17.59 | 2.96 |
| 47 | 45 | -43.7 | 21.2 | SM | B | 16.23 | 16.73 | 17.80 | 3.00 |
| 48 | ... | 21.8 | -47.6 | SM | E | 16.26 | 16.87 | 17.75 | 3.03 |
| 49 | 61 | -12.7 | -1.0 | SM | B | 16.31 | 16.87 | 17.80 | 3.02 |
| 50 | 47 | 114.1 | -121.3 | SM | ... | 16.32 | 16.92 | 17.82 | 3.06 |
| 51 | 50 | 112.8 | -82.5 | SM | ... | 16.35 | 16.95 | 17.91 | 2.96 |
| 52 | 63 | -1.6 | -23.5 | SM | B | 16.36 | 16.96 | 17.89 | 3.00 |
| 53 | ... | 0.3 | -41.1 | ... | B | 16.36 | 16.92 | 17.86 | 2.94 |
| 54 | 49 | 10.1 | -43.0 | ... | E | 16.38 | 16.89 | 17.78 | 2.81 |
| 55 | 66 | -17.3 | 35.9 | SM | L | 16.40 | 17.04 | 17.93 | 2.96 |
| 56 | 55 | 21.5 | 29.0 | SM | E | 16.44 | 17.07 | 17.89 | 2.92 |
| 57 | 62 | 51.5 | -14.7 | ... | E | 16.45 | 17.05 | 17.92 | 2.90 |
| 58 | ... | 3.6 | -41.1 | ... | E | 16.48 | 17.13 | 18.02 | 2.99 |
| 59 | ... | -111.2 | 101.4 | ... | ... | 16.48 | 16.65 | 17.23 | 2.21 |
| 60 | 39 | 24.1 | 41.7 | SM | M | 16.54 | 17.22 | 18.08 | 2.68 |
| 61 | 60 | -12.1 | -60.3 | ... | B | 16.54 | 17.13 | 17.92 | 2.80 |
| 62 | 91 | -0.7 | -44.7 | ... | E | 16.55 | 17.24 | 18.18 | 3.06 |
| 63 | ... | 132.7 | -70.1 | ... | ... | 16.55 | 17.20 | 18.17 | 2.99 |
| 64 | ... | -91.9 | 115.1 | ... | ... | 16.55 | 17.36 | 18.47 | 3.62 |
| 65 | 80 | 2.9 | 8.8 | SM | L | 16.55 | 17.15 | 18.12 | 3.02 |

TABLE 2—*Continued*

| SED | BO | x('') | y('') | M | Type | K | H | J | 7512-K |
|-----|-----|--------|-------|-----|------|-------|-------|-------|--------|
| | 71 | 1.0 | −73.3 | ... | A | 16.56 | 17.13 | 18.11 | 2.87 |
| 67 | 96 | 66.8 | −64.5 | SM | ... | 16.57 | 17.25 | 18.13 | 3.02 |
| 68 | ... | 103.3 | −41.1 | ... | ... | 16.58 | 16.63 | 17.04 | 0.99 |
| 69 | ... | −136.3 | 49.6 | ... | ... | 16.60 | 16.59 | 16.95 | 0.90 |
| 70 | ... | 90.0 | 132.4 | ... | ... | 16.62 | 17.23 | 18.14 | 2.82 |
| 71 | ... | −22.8 | 20.9 | SM | B | 16.63 | 17.23 | 18.12 | 2.94 |
| 72 | 84 | −16.0 | 2.0 | ... | E | 16.65 | 17.24 | 18.16 | 2.88 |
| 73 | ... | −36.5 | 47.3 | ... | ... | 16.66 | 16.91 | 17.44 | 2.30 |
| 74 | 70 | 75.0 | −13.4 | SM | L | 16.67 | 17.29 | 18.14 | 2.83 |
| 75 | ... | −6.5 | −51.8 | ... | A | 16.69 | 17.28 | 18.17 | 2.93 |
| 76 | 106 | 57.7 | −43.4 | SM | E | 16.70 | 17.32 | 18.28 | 3.01 |
| 77 | 75 | 14.0 | −93.2 | SM | L | 16.70 | 17.31 | 18.13 | 2.91 |

TABLE 2—*Continued*

| SED | BO | x(") | y(") | M | Type | K | H | J | 7512-K |
|-----|-----|--------|--------|-----------------|------|-------|-------|-------|--------|
| | ... | -4.2 | -9.5 | SM | L | 16.71 | 17.24 | 18.16 | 2.97 |
| 79 | ... | 5.5 | -45.0 | ... | B | 16.72 | 17.36 | 18.30 | 3.05 |
| 80 | ... | -25.4 | -81.2 | ... | ... | 16.74 | 17.59 | 18.53 | 3.66 |
| 81 | 111 | 40.1 | -2.3 | ... | E | 16.76 | 17.39 | 18.27 | 3.02 |
| 82 | ... | -67.2 | 43.0 | SNM | ... | 16.78 | 17.41 | 18.15 | 2.70 |
| 83 | 79 | 72.4 | -116.7 | SM | ... | 16.78 | 17.37 | 18.20 | 2.71 |
| 84 | 44 | -10.1 | -109.9 | SNM | ... | 16.79 | 17.35 | 18.21 | 2.79 |
| 85 | ... | -84.8 | 60.0 | SNM | * | 16.80 | 16.71 | 16.95 | 0.55 |
| 86 | 119 | 26.7 | -34.2 | ... | L | 16.82 | 17.41 | 18.42 | 3.18 |
| 87 | 99 | -48.2 | 17.6 | SNM | ... | 16.87 | 17.42 | 18.39 | 2.96 |
| 88 | ... | 113.4 | -131.1 | ... | ... | 16.89 | 17.59 | 18.64 | 2.97 |
| 89 | ... | 73.3 | 113.8 | ... | ... | 16.90 | 17.55 | 18.46 | 2.80 |
| 90 | 59 | 119.6 | -109.9 | SNM | ... | 16.90 | 17.49 | 18.23 | 2.46 |
| 91 | ... | -108.6 | 38.8 | SM | ... | 16.91 | 17.44 | 18.42 | 2.85 |
| 92 | 154 | -17.0 | -29.0 | ... | E | 16.91 | 17.44 | 18.20 | 2.97 |
| 93 | 130 | -17.3 | -66.8 | SNM | B | 16.91 | 17.57 | 18.34 | 3.06 |
| 94 | ... | 104.0 | 80.2 | ... | ... | 16.93 | 17.54 | 18.47 | 3.09 |
| 95 | 131 | -29.7 | 34.6 | SM | L | 16.97 | 17.71 | 18.66 | 3.01 |
| 96 | ... | -15.6 | -13.0 | ... | E | 16.99 | 17.61 | 18.41 | 2.86 |
| 97 | 102 | -69.4 | -21.5 | SM | ... | 16.99 | 17.55 | 18.44 | 2.88 |
| 98 | ... | -25.4 | 128.4 | ... | ... | 17.00 | 17.62 | 18.40 | 2.67 |
| 99 | ... | 27.1 | -15.3 | ... | E | 17.00 | 17.69 | 18.59 | 3.04 |
| 100 | 95 | -3.9 | -68.1 | ... | E | 17.01 | 17.52 | 18.31 | 2.72 |
| 101 | 152 | -16.3 | -63.9 | ... | L | 17.02 | 17.74 | 18.47 | 3.04 |
| 102 | 107 | 7.2 | 66.2 | SM | L | 17.05 | 17.61 | 18.53 | 2.81 |
| 103 | ... | -13.7 | 118.0 | ... | ... | 17.06 | 17.81 | 18.63 | 2.99 |
| 104 | 190 | 29.7 | -7.8 | ... | E | 17.07 | 17.81 | 18.67 | 3.06 |
| 105 | 56 | -121.9 | 7.2 | SNM | ... | 17.10 | 17.46 | 18.24 | 2.32 |
| 106 | 108 | -64.2 | -76.9 | SM | ... | 17.12 | 17.72 | 18.62 | 2.78 |
| 107 | 136 | 5.9 | -51.5 | SM | E | 17.12 | 17.70 | 18.52 | 2.83 |
| 108 | 230 | -5.2 | -12.4 | ... | E | 17.12 | 17.82 | 18.83 | 3.19 |
| 109 | 149 | 52.2 | 19.2 | SM | A | 17.13 | 17.64 | 18.54 | 2.89 |
| 110 | ... | 8.5 | -30.3 | ... | ... | 17.13 | 17.78 | 18.66 | 2.70 |
| 111 | 129 | 26.4 | -44.0 | ... | C | 17.14 | 17.69 | 18.61 | 2.80 |
| 112 | ... | 109.9 | -76.0 | ... | ... | 17.16 | 17.81 | 18.81 | 3.06 |
| 113 | ... | 2.0 | 92.3 | ... | ... | 17.17 | 17.72 | 18.58 | 2.77 |
| 114 | 165 | 30.0 | -32.6 | SM | C | 17.17 | 17.75 | 18.74 | 2.85 |
| 115 | 105 | 28.4 | -20.5 | ... | E | 17.20 | 17.76 | 18.56 | 2.62 |
| 116 | 113 | -120.0 | -30.6 | SNM | ... | 17.20 | 17.71 | 18.55 | 2.72 |
| 117 | 167 | -27.4 | -74.7 | SM | A | 17.22 | 17.99 | 18.69 | 3.04 |
| 118 | ... | 77.9 | 103.7 | ... | ... | 17.24 | 17.86 | 18.58 | 2.66 |
| 119 | ... | 71.7 | 110.2 | ... | ... | 17.27 | 18.03 | 18.86 | 2.90 |
| 120 | ... | 108.2 | 126.2 | ... | ... | 17.28 | 18.22 | 19.35 | 3.82 |
| 121 | 161 | 39.4 | -25.1 | ... | L | 17.28 | 17.86 | 18.81 | 2.80 |
| 122 | 142 | -14.0 | -49.2 | SM | L | 17.31 | 17.82 | 18.63 | 2.82 |
| 123 | 128 | -25.1 | 31.9 | SM | M | 17.32 | 17.98 | 18.75 | 2.50 |
| 124 | ... | 15.0 | -42.4 | SNM | D | 17.32 | 18.04 | 18.90 | 2.93 |
| 125 | 153 | 36.5 | 26.7 | ... | E | 17.33 | 17.79 | 18.89 | 2.96 |
| 126 | 133 | 19.2 | -17.0 | SM | L | 17.37 | 18.03 | 19.14 | 2.88 |
| 127 | 145 | -94.5 | 12.4 | SM | ... | 17.37 | 17.88 | 18.83 | 2.66 |
| 128 | ... | 73.3 | 67.2 | ... | ... | 17.39 | 18.15 | 19.10 | 3.21 |
| 129 | 166 | -38.5 | 2.9 | SM ₄ | L | 17.40 | 17.95 | 18.64 | 2.61 |
| 130 | 203 | 70.1 | -21.5 | ... | E | 17.41 | 18.18 | 18.97 | 3.02 |
| 131 | ... | 128.1 | 129.1 | ... | ... | 17.42 | 18.02 | 18.81 | 2.46 |
| 132 | ... | -8.5 | -87.4 | ... | A | 17.42 | 18.15 | 18.96 | 2.90 |
| 133 | 219 | 16.3 | -4.2 | ... | B | 17.44 | 18.34 | 19.52 | 3.17 |

TABLE 2—*Continued*

| SED | BO | x(") | y(") | M | Type | K | H | J | 7512-K |
|-----|-----|--------|--------|-----|------|-------|-------|-------|--------|
| | ... | -132.0 | -58.0 | ... | ... | 17.53 | 18.08 | 19.04 | 2.73 |
| 137 | ... | -92.9 | 52.5 | ... | ... | 17.54 | 18.19 | 19.13 | 3.02 |
| 138 | ... | 113.8 | 28.4 | ... | ... | 17.54 | 18.15 | 19.10 | 2.66 |
| 139 | ... | 79.2 | 16.6 | ... | L | 17.55 | 18.00 | 18.81 | 2.62 |
| 140 | ... | 116.1 | 65.5 | ... | ... | 17.55 | 18.17 | 19.13 | 3.45 |
| 141 | ... | -1.6 | 136.6 | ... | ... | 17.55 | 18.14 | 19.36 | 2.99 |
| 142 | 163 | -6.5 | 60.3 | SM | B | 17.57 | 18.33 | 19.05 | 2.72 |
| 143 | ... | 79.5 | 109.5 | ... | ... | 17.58 | 18.10 | 18.67 | 2.54 |
| 144 | ... | -63.9 | 28.7 | ... | B | 17.59 | 18.45 | 19.02 | 2.94 |
| 145 | 213 | 42.1 | 4.2 | ... | L | 17.59 | 18.04 | 18.92 | 2.86 |
| 146 | ... | 140.2 | 22.5 | ... | ... | 17.61 | 18.25 | 18.91 | 2.67 |
| 147 | ... | -20.9 | 35.9 | ... | ... | 17.62 | 17.98 | 18.41 | 2.43 |
| 148 | 137 | 73.7 | -69.8 | SM | ... | 17.62 | 18.33 | 19.03 | 2.37 |
| 149 | ... | -46.0 | 114.4 | ... | ... | 17.63 | 18.09 | 19.09 | 2.69 |
| 150 | ... | -8.5 | 7.8 | ... | ... | 17.64 | 18.37 | 19.17 | 3.38 |
| 151 | ... | 2.6 | -9.1 | ... | E | 17.65 | 18.24 | 18.95 | 2.96 |
| 152 | 16 | -90.6 | -51.2 | SNM | * | 17.65 | 17.52 | 17.53 | 0.50 |
| 153 | ... | 82.2 | -142.1 | ... | ... | 17.66 | 18.56 | 19.12 | 3.16 |
| 154 | ... | -2.0 | -90.0 | ... | A | 17.69 | 18.38 | 19.24 | 2.89 |
| 155 | ... | 112.5 | -93.2 | ... | ... | 17.70 | 18.60 | 19.38 | 2.93 |
| 156 | ... | -84.1 | 87.0 | ... | ... | 17.71 | 18.35 | 19.03 | 2.62 |
| 157 | 181 | 9.8 | -59.7 | ... | B | 17.72 | 18.19 | 19.14 | 2.67 |
| 158 | ... | -68.8 | -35.2 | ... | ... | 17.74 | 18.53 | 19.47 | 2.94 |
| 159 | ... | -34.2 | -5.5 | ... | L | 17.76 | 18.25 | 19.05 | 2.41 |
| 160 | ... | -132.4 | 38.5 | ... | ... | 17.80 | 18.72 | 20.02 | 3.32 |
| 161 | ... | -35.5 | -105.3 | ... | ... | 17.81 | 18.25 | 18.94 | 2.32 |
| 162 | ... | -15.0 | 111.5 | ... | ... | 17.82 | 18.65 | 19.51 | 2.86 |
| 163 | 197 | 13.7 | 78.6 | ... | E | 17.83 | 18.39 | 19.38 | 2.73 |
| 164 | ... | -140.5 | 92.3 | ... | ... | 17.83 | 18.37 | 19.43 | 2.86 |
| 165 | ... | 81.8 | -86.7 | ... | ... | 17.87 | 18.55 | 19.32 | 2.93 |
| 166 | ... | 126.2 | -136.3 | ... | ... | 17.87 | 18.48 | 20.10 | 3.22 |
| 167 | ... | 107.3 | -83.1 | ... | ... | 17.89 | 18.66 | 19.05 | 2.44 |
| 168 | ... | 60.6 | -142.1 | ... | ... | 17.89 | 19.31 | 19.72 | 3.20 |
| 169 | ... | -40.1 | -114.4 | ... | ... | 17.90 | 18.22 | 19.16 | 2.21 |
| 170 | 236 | 70.7 | 8.2 | ... | B | 17.91 | 18.58 | 19.61 | 2.90 |
| 171 | ... | 75.0 | 104.6 | ... | ... | 17.92 | 19.19 | 19.26 | 2.44 |
| 172 | 257 | 47.3 | 28.0 | ... | B | 17.92 | 18.45 | 19.66 | 2.91 |
| 173 | 226 | 36.2 | -26.7 | ... | L | 17.93 | 18.55 | 19.07 | 2.41 |
| 174 | ... | -71.7 | -134.3 | ... | ... | 17.94 | 18.77 | 19.96 | 3.32 |
| 175 | ... | 140.5 | -88.3 | ... | ... | 17.94 | 18.64 | 19.59 | 2.92 |
| 176 | ... | -105.6 | -122.2 | ... | ... | 17.95 | 18.87 | 20.33 | 4.01 |
| 177 | 244 | 55.1 | -60.3 | ... | L | 17.97 | 18.70 | 19.57 | 2.92 |
| 178 | 311 | 42.4 | -22.2 | SM | E | 17.98 | 18.57 | 19.26 | 2.96 |
| 179 | ... | 55.7 | 57.7 | ... | ... | 17.98 | 18.81 | 20.15 | 4.32 |

^aJ2000: 02^h39^m52^s50, -01°34' 20''

TABLE 3
ABELL 851

| SED | DG | x(") | y(") | M | Type | K | H | J | 7843-K |
|----------------|-----|--------|--------|-----|------|-------|-------|-------|--------|
| 1 | ... | -110.2 | -95.5 | ... | * | 13.43 | 13.51 | 13.83 | 0.88 |
| 2 | ... | 89.7 | 111.2 | ... | * | 14.12 | 14.16 | 14.53 | 0.77 |
| 3 | ... | 109.9 | -102.7 | ... | ... | 14.21 | 14.63 | 15.40 | 2.31 |
| 4 | ... | 64.5 | -69.8 | ... | * | 14.21 | 14.25 | 14.58 | 0.75 |
| 5 | ... | 131.7 | 14.3 | ... | ... | 14.89 | 15.30 | 16.05 | 2.25 |
| 6 | ... | -94.5 | 139.2 | ... | ... | 15.53 | 16.19 | 17.02 | 2.72 |
| 7 ^a | 311 | 0.0 | 0.0 | SM | E | 15.55 | 16.21 | 17.05 | 2.79 |
| 8 | 439 | -16.3 | 47.3 | SM | M | 15.68 | 16.26 | 17.14 | 2.58 |
| 9 | 367 | -12.4 | 21.2 | SM | E | 15.86 | 16.55 | 17.40 | 2.85 |
| 10 | 366 | 4.9 | 21.5 | SM | E | 15.86 | 16.46 | 17.35 | 2.78 |
| 11 | 296 | -22.2 | -8.5 | ... | B | 15.86 | 16.63 | 17.67 | 3.41 |
| 12 | 396 | 104.0 | 34.9 | SNM | L | 15.88 | 16.46 | 17.30 | 2.61 |
| 13 | 236 | 65.9 | -31.0 | ... | * | 15.96 | 16.19 | 16.78 | 2.08 |
| 14 | ... | -69.8 | 22.8 | ... | ... | 15.99 | 16.42 | 17.09 | 2.13 |
| 15 | 460 | 75.0 | 59.7 | SM | E | 15.99 | 16.58 | 17.49 | 2.81 |
| 16 | ... | -28.4 | -13.0 | ... | ... | 16.00 | 16.59 | 17.44 | 2.75 |
| 17 | ... | 58.4 | 139.9 | ... | ... | 16.01 | 16.62 | 17.59 | 2.88 |
| 18 | ... | -88.3 | 135.6 | ... | ... | 16.10 | 16.78 | 17.65 | 2.75 |
| 19 | 360 | -7.8 | 18.6 | SM | A | 16.14 | 16.80 | 17.61 | 2.70 |
| 20 | ... | 135.3 | -7.2 | ... | ... | 16.18 | 16.74 | 17.59 | 2.60 |
| 21 | ... | 89.3 | -102.0 | ... | ... | 16.18 | 16.36 | 16.97 | 2.06 |
| 22 | 270 | 37.2 | -17.3 | SNM | B | 16.31 | 16.88 | 17.60 | 2.47 |
| 23 | ... | -112.1 | 158.8 | ... | ... | 16.32 | 17.05 | 17.72 | 9.85 |
| 24 | ... | 21.5 | 87.7 | ... | ... | 16.32 | 16.88 | 17.88 | 2.65 |
| 25 | ... | 45.0 | 129.7 | ... | ... | 16.34 | 16.99 | 17.83 | 2.63 |
| 26 | 398 | 88.0 | 34.9 | SNM | E | 16.35 | 17.00 | 17.91 | 2.88 |
| 27 | ... | -11.7 | -109.2 | ... | ... | 16.39 | 17.01 | 17.82 | 2.65 |
| 28 | ... | 135.6 | -17.6 | ... | ... | 16.42 | 16.96 | 17.86 | 2.68 |
| 29 | ... | -105.3 | 16.6 | ... | ... | 16.44 | 17.10 | 17.92 | 2.65 |
| 30 | 393 | 52.2 | 33.3 | SM | E | 16.45 | 17.06 | 17.95 | 2.77 |
| 31 | ... | 5.2 | 127.8 | ... | ... | 16.46 | 16.98 | 17.93 | 2.51 |
| 32 | ... | -126.5 | 109.2 | ... | ... | 16.47 | 17.12 | 18.14 | 2.98 |
| 33 | 241 | 4.2 | -28.4 | ... | L | 16.47 | 17.10 | 18.01 | 2.70 |
| 34 | ... | 4.6 | 95.8 | ... | ... | 16.48 | 16.56 | 17.19 | 1.51 |
| 35 | 188 | -19.9 | -52.2 | ... | A | 16.53 | 17.06 | 17.97 | 2.56 |
| 36 | ... | 65.2 | 124.9 | ... | ... | 16.57 | 17.26 | 18.32 | 3.15 |
| 37 | ... | 43.4 | -21.2 | ... | * | 16.60 | 16.76 | 17.06 | 0.87 |
| 38 | 436 | 38.1 | 47.6 | ... | L | 16.64 | 17.32 | 18.24 | 2.72 |
| 39 | ... | 38.8 | 98.5 | ... | ... | 16.66 | 17.32 | 18.10 | 2.45 |
| 40 | 427 | 113.1 | 45.3 | SM | E | 16.66 | 17.21 | 18.19 | 2.68 |
| 41 | 157 | -4.9 | -66.5 | SM | A | 16.66 | 17.31 | 18.17 | 2.80 |
| 42 | ... | -108.2 | 153.9 | ... | ... | 16.71 | 17.28 | 18.12 | 2.53 |
| 43 | ... | -55.4 | -47.6 | ... | ... | 16.71 | 16.83 | 17.43 | 1.54 |
| 44 | 397 | 42.7 | 33.6 | ... | L | 16.76 | 17.40 | 18.31 | 2.90 |
| 45 | 206 | 6.2 | -44.7 | ... | E | 16.76 | 17.55 | 18.43 | 2.84 |
| 46 | ... | -17.9 | 121.6 | ... | ... | 16.78 | 16.80 | 17.40 | 1.36 |
| 47 | 422 | -17.9 | 40.4 | SM | L | 16.80 | 17.42 | 18.18 | 2.57 |
| 48 | 226 | 17.3 | -35.9 | ... | L | 16.81 | 17.44 | 18.37 | 2.75 |

TABLE 3—*Continued*

| SED | DG | x(") | y(") | M | Type | K | H | J | 7843-K |
|-----|-----|--------|--------|-----|------|-------|-------|-------|--------|
| | 234 | 73.0 | −31.3 | SNM | B | 16.82 | 17.48 | 18.26 | 2.69 |
| 50 | 310 | 91.3 | 1.6 | SM | E | 16.82 | 17.44 | 18.33 | 2.73 |
| 51 | 282 | −20.9 | −13.4 | ... | B | 16.82 | 17.46 | 18.37 | 2.92 |
| 52 | 519 | −6.5 | 76.0 | SM | ... | 16.83 | 17.42 | 18.35 | 2.83 |
| 53 | ... | −51.8 | 100.7 | ... | ... | 16.84 | 17.39 | 18.24 | 2.70 |
| 54 | 349 | 78.2 | 16.6 | SNM | L | 16.86 | 17.51 | 18.32 | 2.58 |
| 55 | 279 | −14.0 | −14.3 | SM | L | 16.94 | 17.58 | 18.58 | 2.76 |
| 56 | ... | 54.4 | −120.9 | SNM | ... | 17.00 | 17.93 | 19.07 | 3.53 |
| 57 | ... | −123.2 | 5.9 | ... | ... | 17.02 | 17.42 | 18.32 | 2.48 |
| 58 | 303 | 99.8 | −1.6 | ... | L | 17.04 | 17.59 | 18.52 | 2.62 |
| 59 | ... | −62.3 | 137.9 | ... | ... | 17.06 | 17.78 | 18.61 | 2.76 |
| 60 | ... | 31.6 | 94.5 | ... | ... | 17.08 | 17.68 | 18.49 | 2.68 |
| 61 | ... | −82.8 | 125.8 | ... | ... | 17.09 | 17.74 | 18.65 | 2.71 |
| 62 | ... | −17.9 | −89.0 | ... | ... | 17.09 | 17.85 | 18.89 | 3.18 |

TABLE 3—*Continued*

| SED | DG | x(") | y(") | M | Type | K | H | J | 7843-K |
|-----|-----|--------|--------|-----------------|------|-------|-------|-------|--------|
| | ... | 1.0 | 62.6 | ... | ... | 17.11 | 17.18 | 17.73 | 1.66 |
| 64 | ... | -29.3 | 20.9 | ... | ... | 17.12 | 17.77 | 18.52 | 2.52 |
| 65 | 320 | 26.1 | 3.3 | SM | M | 17.14 | 17.73 | 18.65 | 2.52 |
| 66 | ... | 57.4 | 150.3 | ... | ... | 17.15 | 17.95 | 18.67 | 2.67 |
| 67 | ... | 51.2 | -119.0 | ... | ... | 17.15 | 18.17 | 19.00 | 3.26 |
| 68 | ... | -53.5 | 129.7 | ... | ... | 17.16 | 17.70 | 18.56 | 2.39 |
| 69 | ... | -108.6 | 67.5 | ... | ... | 17.19 | 17.70 | 18.37 | 2.37 |
| 70 | ... | -129.7 | 105.3 | ... | ... | 17.20 | 18.10 | 18.87 | 3.13 |
| 71 | ... | 156.5 | 140.5 | ... | ... | 17.20 | 17.93 | 18.90 | 9.37 |
| 72 | ... | 23.8 | 143.8 | ... | ... | 17.21 | 17.90 | 18.50 | 2.28 |
| 73 | 381 | 60.0 | 27.4 | ... | L | 17.22 | 17.95 | 18.84 | 2.81 |
| 74 | ... | -4.2 | 115.4 | ... | ... | 17.25 | 17.80 | 18.78 | 2.49 |
| 75 | 135 | 72.0 | -78.9 | SM | B | 17.26 | 17.74 | 18.64 | 2.51 |
| 76 | 432 | -0.3 | 45.3 | SM | L | 17.26 | 18.14 | 18.85 | 2.84 |
| 77 | ... | -37.2 | -30.6 | ... | ... | 17.26 | 17.82 | 18.66 | 2.65 |
| 78 | 243 | -6.5 | -28.0 | ... | D | 17.27 | 17.79 | 18.63 | 2.39 |
| 79 | ... | -51.8 | 48.2 | ... | ... | 17.27 | 17.66 | 18.71 | 2.73 |
| 80 | ... | 64.2 | 67.5 | ... | ... | 17.30 | 17.72 | 18.49 | 2.56 |
| 81 | 191 | 54.4 | -50.5 | SM | L | 17.30 | 18.03 | 18.84 | 2.64 |
| 82 | ... | -127.5 | -33.6 | ... | ... | 17.31 | 17.99 | 18.86 | 2.76 |
| 83 | 511 | 23.8 | 73.7 | SM | ... | 17.33 | 18.14 | 18.81 | 2.42 |
| 84 | ... | -33.3 | 4.6 | ... | ... | 17.33 | 17.90 | 18.80 | 2.65 |
| 85 | ... | 98.5 | 116.7 | ... | ... | 17.34 | 17.90 | 18.76 | 2.42 |
| 86 | 244 | 8.8 | -27.7 | SNM | A | 17.34 | 17.97 | 18.89 | 2.81 |
| 87 | 451 | 1.3 | 52.8 | SM | M | 17.35 | 18.07 | 18.93 | 2.61 |
| 88 | ... | -69.4 | 112.5 | ... | ... | 17.35 | 17.88 | 18.60 | 1.89 |
| 89 | ... | 58.7 | 125.8 | ... | ... | 17.39 | 18.11 | 18.89 | 2.72 |
| 90 | ... | -86.4 | 119.3 | ... | ... | 17.39 | 17.67 | 18.16 | 2.24 |
| 91 | 246 | 101.1 | -24.5 | ... | L | 17.39 | 17.94 | 18.94 | 2.92 |
| 92 | 390 | -23.5 | 31.0 | SM | A | 17.41 | 17.95 | 18.74 | 2.45 |
| 93 | 80 | 55.4 | -116.7 | SM | ... | 17.42 | 18.17 | 18.93 | 2.66 |
| 94 | ... | 81.8 | -124.5 | ... | ... | 17.43 | 18.21 | 19.27 | 6.58 |
| 95 | 321 | -9.5 | 3.9 | SM | L | 17.44 | 18.00 | 18.72 | 2.56 |
| 96 | ... | 16.3 | 122.2 | ... | ... | 17.44 | 18.10 | 19.12 | 2.76 |
| 97 | ... | -47.6 | 45.3 | ... | ... | 17.45 | 18.03 | 19.03 | 2.85 |
| 98 | 348 | 106.6 | 16.3 | ... | C | 17.47 | 18.36 | 19.41 | 2.49 |
| 99 | 186 | 119.3 | -47.6 | ... | B | 17.47 | 18.60 | 19.33 | 3.59 |
| 100 | ... | -55.1 | -106.0 | ... | ... | 17.50 | 17.93 | 18.41 | 2.74 |
| 101 | ... | 125.2 | 77.3 | ... | ... | 17.51 | 18.20 | 18.90 | 2.75 |
| 102 | 471 | 6.8 | 60.3 | SM | C | 17.52 | 18.29 | 19.05 | 2.41 |
| 103 | ... | 122.2 | 67.8 | ... | ... | 17.53 | 18.16 | 18.95 | 2.47 |
| 104 | 408 | 2.9 | 35.9 | ... | L | 17.56 | 18.85 | 19.52 | 3.28 |
| 105 | ... | -100.7 | 131.4 | ... | ... | 17.57 | 18.20 | 19.21 | 2.76 |
| 106 | ... | 122.2 | 90.6 | ... | ... | 17.58 | 18.12 | 18.89 | 2.61 |
| 107 | ... | -53.5 | -25.1 | ... | ... | 17.58 | 18.12 | 19.21 | 3.05 |
| 108 | ... | 49.9 | 132.4 | ... | ... | 17.58 | 18.07 | 19.00 | 2.70 |
| 109 | ... | -47.6 | 18.3 | ... | ... | 17.60 | 18.10 | 19.01 | 2.61 |
| 110 | 380 | 92.3 | 28.4 | ... | A | 17.60 | 18.28 | 19.19 | 2.69 |
| 111 | ... | -62.9 | 118.0 | ... | ... | 17.61 | 18.08 | 18.80 | 2.20 |
| 112 | 458 | 4.2 | 55.4 | ... | E | 17.62 | 18.32 | 18.85 | 2.60 |
| 113 | 410 | -6.8 | 36.5 | ... | L | 17.62 | 18.27 | 19.06 | 2.68 |
| 114 | 338 | -21.8 | 8.8 | ... | A | 17.62 | 18.42 | 19.06 | 2.83 |
| 115 | 225 | 101.4 | -33.9 | SM ⁸ | C | 17.64 | 18.02 | 19.33 | 2.95 |
| 116 | 169 | 12.7 | -60.6 | ... | L | 17.66 | 18.59 | 19.16 | 2.64 |
| 117 | ... | 13.4 | 129.7 | ... | ... | 17.66 | 18.19 | 19.02 | 2.09 |
| 118 | ... | -133.0 | 34.9 | ... | ... | 17.67 | 18.07 | 19.13 | 2.83 |

TABLE 3—*Continued*

| SED | DG | x(") | y(") | M | Type | K | H | J | 7843–K |
|-----|-----|-------|--------|-----|------|-------|-------|-------|--------|
| | ... | −88.7 | −35.9 | ... | ... | 17.75 | 17.85 | 18.34 | 1.86 |
| 125 | ... | 36.5 | −127.1 | ... | ... | 17.76 | 18.55 | 19.39 | 7.45 |
| 126 | ... | −92.6 | −65.5 | ... | ... | 17.78 | 18.84 | 19.90 | 3.28 |
| 127 | ... | 132.0 | −41.7 | ... | ... | 17.78 | 18.51 | 19.51 | 2.79 |
| 128 | ... | 83.1 | −85.4 | ... | ... | 17.79 | 18.77 | 19.61 | 2.99 |
| 129 | 419 | 46.6 | 41.1 | ... | L | 17.79 | 18.56 | 19.32 | 2.58 |
| 130 | 403 | 59.0 | 35.9 | SNM | C | 17.80 | 18.65 | 19.20 | 2.47 |
| 131 | ... | 91.9 | −90.6 | ... | ... | 17.80 | 18.46 | 19.44 | 2.77 |
| 132 | 457 | 97.5 | 57.7 | ... | E | 17.80 | 18.63 | 19.85 | 2.85 |
| 133 | 420 | 38.8 | 41.1 | SNM | B | 17.80 | 18.62 | 19.33 | 2.54 |
| 134 | ... | −63.9 | −35.9 | ... | ... | 17.81 | 17.86 | 18.66 | 1.75 |
| 135 | ... | −70.7 | 97.1 | ... | ... | 17.82 | 18.49 | 19.43 | 2.94 |
| 136 | 322 | 31.3 | 5.9 | ... | C | 17.83 | 18.70 | 19.55 | 2.90 |
| 137 | 441 | 70.4 | 50.2 | SM | A | 17.84 | 18.32 | 18.95 | 2.36 |
| 138 | 153 | 3.9 | −68.5 | ... | ... | 17.88 | 18.41 | 19.23 | 2.38 |
| 139 | 176 | −19.2 | −59.0 | ... | B | 17.90 | 18.34 | 19.16 | 2.75 |
| 140 | ... | 94.9 | 102.4 | ... | ... | 17.90 | 18.28 | 19.32 | 2.10 |
| 141 | ... | 56.7 | −94.9 | ... | ... | 17.91 | 18.76 | 19.73 | 2.84 |
| 142 | ... | 144.4 | 136.3 | ... | ... | 17.92 | 18.48 | 19.42 | 2.54 |
| 143 | ... | −86.7 | −107.6 | ... | ... | 17.93 | 19.21 | 20.12 | 4.95 |
| 144 | ... | −18.6 | 89.3 | ... | ... | 17.93 | 18.64 | 19.41 | 2.68 |
| 145 | 143 | 93.6 | −73.7 | ... | M | 17.94 | 18.01 | 18.62 | 1.98 |
| 146 | 375 | −3.3 | 23.8 | ... | L | 17.94 | 18.50 | 19.33 | 2.67 |
| 147 | 409 | 28.7 | 37.2 | ... | C | 17.94 | 18.74 | 19.63 | 2.81 |
| 148 | ... | 102.4 | −107.6 | ... | ... | 17.95 | 18.58 | 19.53 | 2.69 |
| 149 | 356 | 37.8 | 17.6 | ... | L | 17.97 | 18.52 | 19.69 | 2.75 |
| 150 | ... | 28.4 | −11.1 | ... | ... | 17.97 | 18.66 | 19.42 | 2.76 |
| 151 | 314 | 13.4 | 1.3 | ... | L | 17.98 | 18.53 | 19.49 | 2.53 |
| 152 | 299 | 22.2 | −5.2 | ... | L | 17.98 | 18.60 | 19.54 | 2.79 |
| 153 | ... | −59.0 | −57.0 | ... | ... | 17.99 | 18.27 | 19.35 | 2.60 |
| 154 | ... | 65.5 | 151.6 | ... | ... | 17.99 | 19.00 | 19.67 | 3.36 |

^aJ2000: 09^h42^m56^s.89, 46°58′ 44″

TABLE 4
SYSTEMATIC ERRORS

| Type | Amount | Affects |
|--|--------|------------------|
| Optical image blur ^a | 0.01 | our optical mag |
| Color gradient correction ^b | 0.02 | Coma $V - H$ |
| k -correction ^c | 0.01 | Coma $V - H$ |
| Bower zeropoint uncertainty ^d | 0.034 | Coma $V - H$ |
| SED zeropoint uncertainty ^e | 0.035 | our optical- K |
| Reddening correction ^f | 0.02 | our optical- K |

^aDetermined using simulated galaxies

^bAssumes gradients are constant with radius and constant with luminosity

^cDetermined using BC model elliptical; very similar value for model disk galaxies

^dAs given by Bower et al. (1992)

^eUsing estimates from Burstein & Heiles (1982)

TABLE 5

MEDIAN OPTICAL- K COLOR RESIDUALS FROM COMA AS A FUNCTION OF MORPHOLOGY FOR IR/HST SAMPLES

| Type | Abell 370 | Abell 851 |
|-------|------------------|------------------|
| E/SO | -0.13 ± 0.15 | -0.18 ± 0.15 |
| Sa/Sb | -0.11 ± 0.11 | -0.26 ± 0.16 |
| Sc/Sd | -0.19 ± 0.07 | -0.38 ± 0.25 |